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14. ABSTRACT

The flow and mixing properties of confined transverse jets are relevant to a myriad of combustion devices ranging from propulsion to energy generation and chemical processing. The current effort focuses on understanding the mixing process between a transverse jet mixing in a confined system. The current study involves the simulation of a single confined transverse jet configuration under matched conditions of a companion experiment. The main flow Reynolds number considered is in the range of 25000 - 53000 and the jet-to-main flow momentum flux ratio is varied from 3.2 -14.3. The momentum and scalar mixing is investigated through the solution of the Reynolds-Averaged Navier Stokes (RANS) equations. The mean scalar mixing characteristics are compared to experimental data. The turbulence model that is used is the low Reynolds number k-ϵ model. Due to demonstrated symmetry, only a one-half section of the geometry is considered. All numerical simulations capture salient flow structures such as the counter-rotating vortex pair (CRVP). The current investigation shows the numerical simulations predict the experimental data with a good degree of accuracy.

15. SUBJECT TERMS

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AIAA
The World's Forum for Aerospace Leadership

Numerical and Experimental Investigation of Confined Turbulent Multiple Transverse Jets

29 July 2014
Presented to: AIAA Propulsion and Energy, Cleveland, Ohio

Farhad Davoudzadeh, Ph.D. – Air Force Research Laboratory
David Forliti, Ph.D. - Sierra Lobo, Inc.

Outline

- Objectives
- Jet in Crossflow characteristics
- ONERA Air-to-air Experimental configuration and Computational Setup
- AFRL's water-to-water Experimental configuration and Computational Setup
- Simulation matrix, computational results
- Comparative Analysis Results
- Summary & planned work

Objectives

- Investigate mixing characteristics of propellants in combustors
- CFD support for the in-house Themis project
- Provide numerical data for theoretical developments

Project Themis

- In-house combustion device research within the Combustion Devices Branch (RQRC) of AFRL

- Focuses on investigation of LOX/Hydrocarbon high
- pressure combustion devices through:

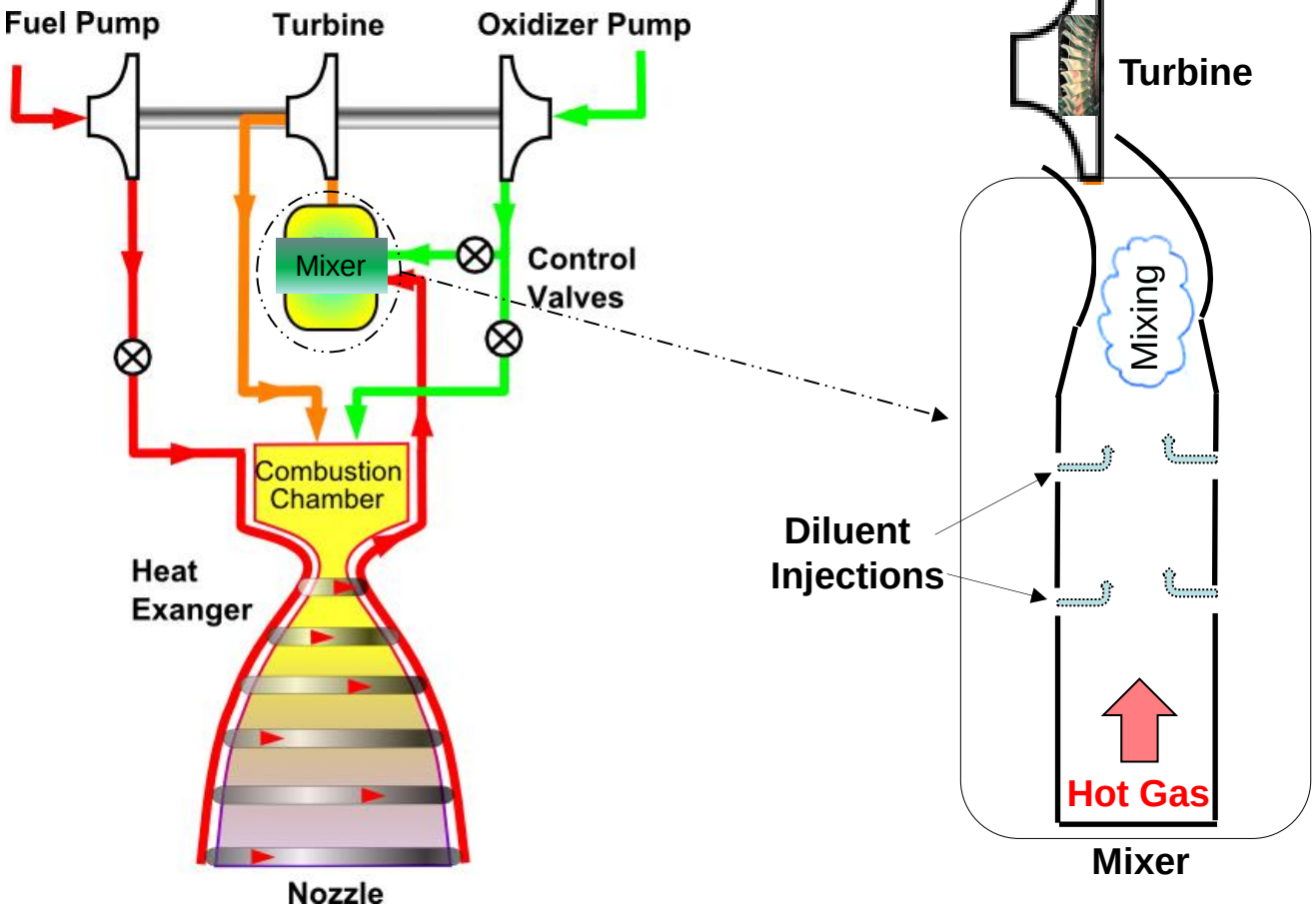
  - Theory development
  - Modeling and simulation
  - Subscale experimentation at reacting and inert conditions:

    - Design & test a 10k lbf combustor for liquid propellants

      - Requires good mixing of variable density propellants
      - Temperature uniformity
      - Concentration uniformity

      Jet in Crossflow

Staged Combustion Cycle Rocket Engine



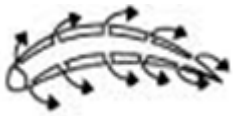
Staged Combustion cycle

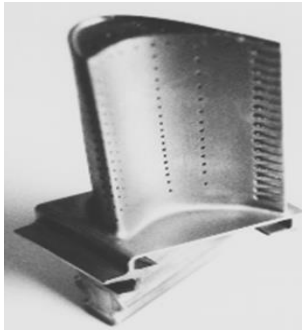
Temperature Distribution
On the Turbine Blades

Jet in Cross Flow Characteristics

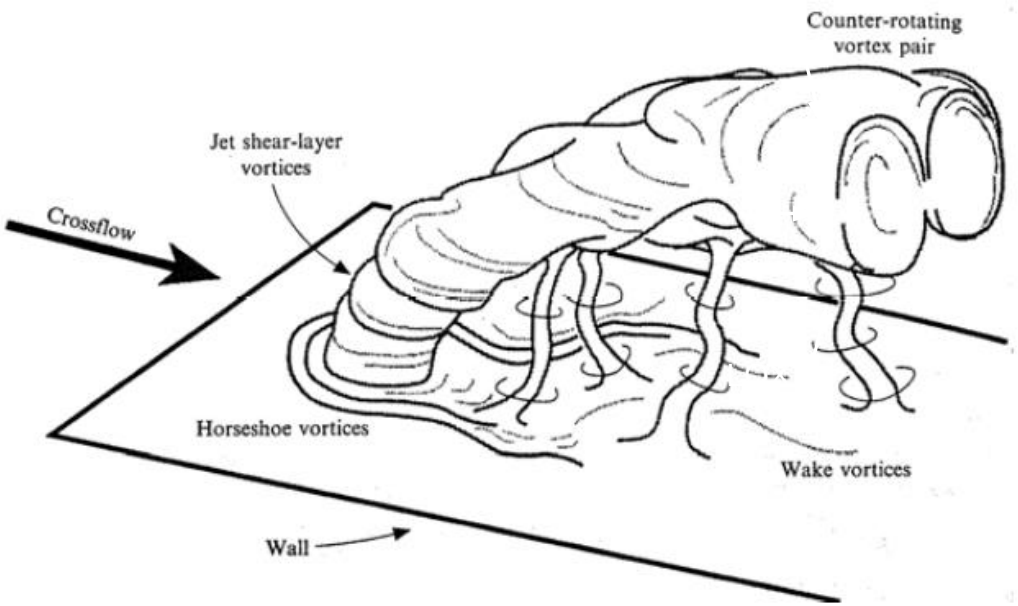
Complex flow with multiple engineering applications:

- Gas turbine combustors
- Film cooling of turbine blades
- Air pollution
- Chimney emissions
- Industrial burners
- Chemical mixing
- Wastewater discharges





Jet in Cross Flow Characteristics



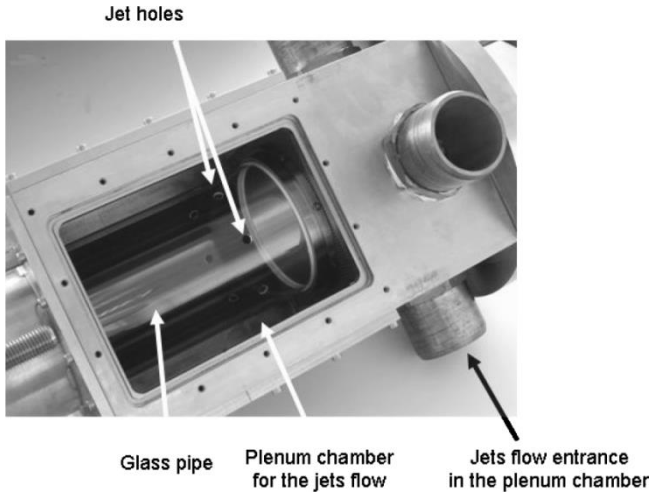
Adapted from Fric and Roshko (1994)

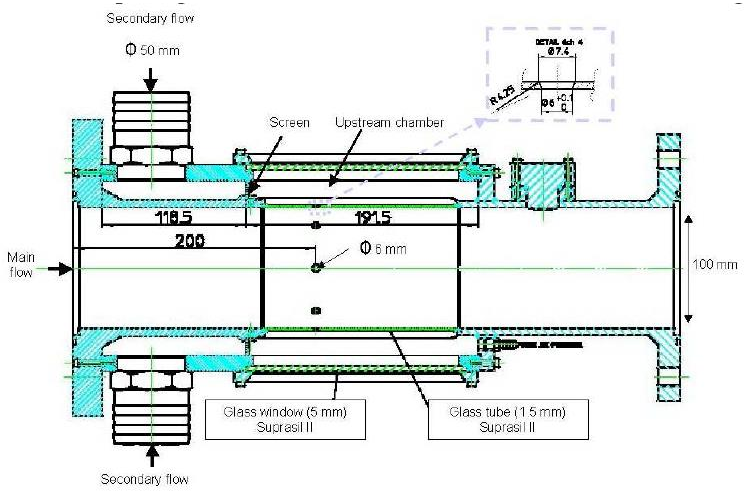
Previous Numerical Work at AFRL: Air-to-Air Experimental Configuration

Conduct a validation study for a baseline case:

- Experimental data available
- Unity density ratio
- Multiple confined transverse jets
- Single phase/component

ONERA experimental/LES studies of an eight jet mixing chamber





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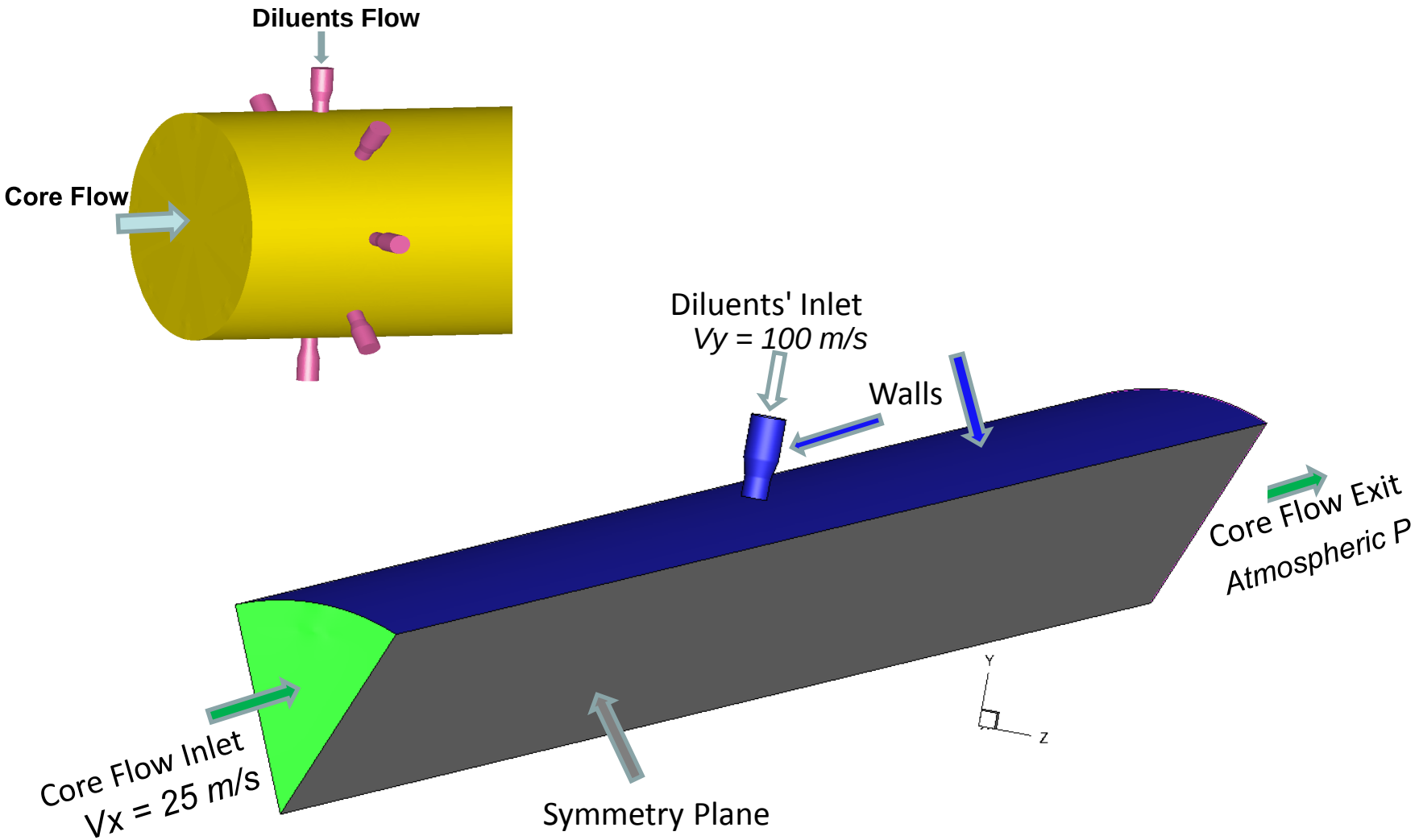
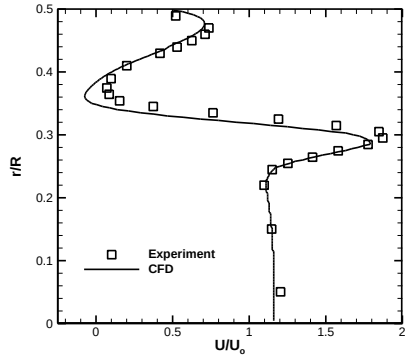
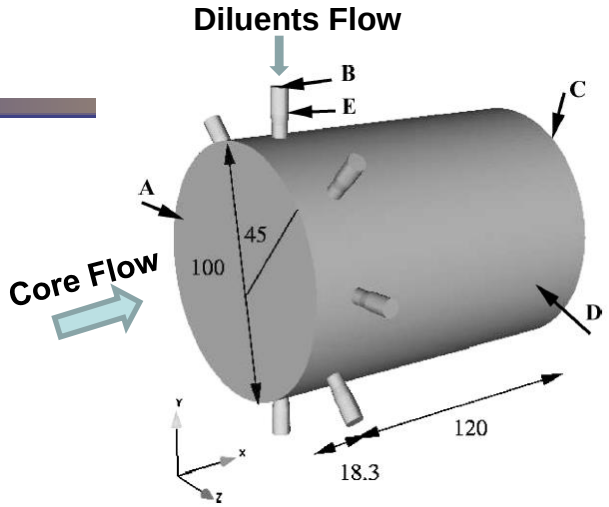
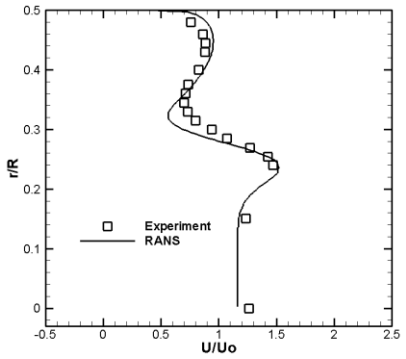


Air-to-Air Numerical and Experimental Comparisons

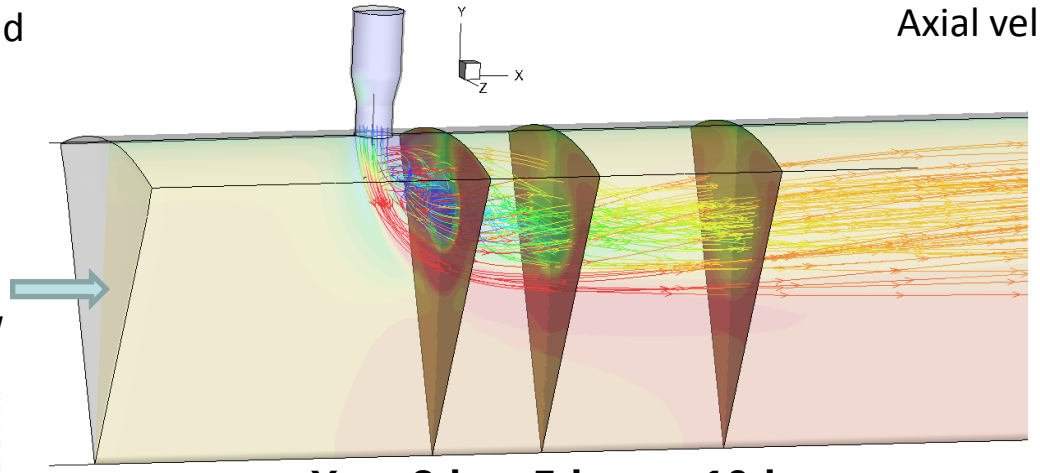


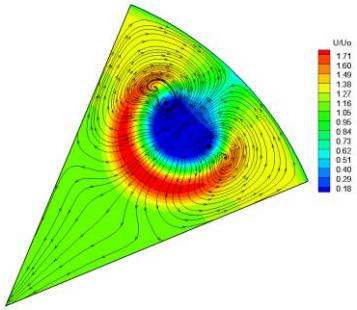
Axial velocity profile, x = 2d



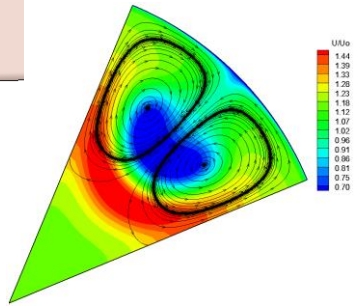


Axial velocity profile, x = 5d





Axial velocity Contours, x = 2d



Axial velocity contours, x = 5d

Air-to-Air Experimental Data Versus Computational Results: Jet Concentration Profiles

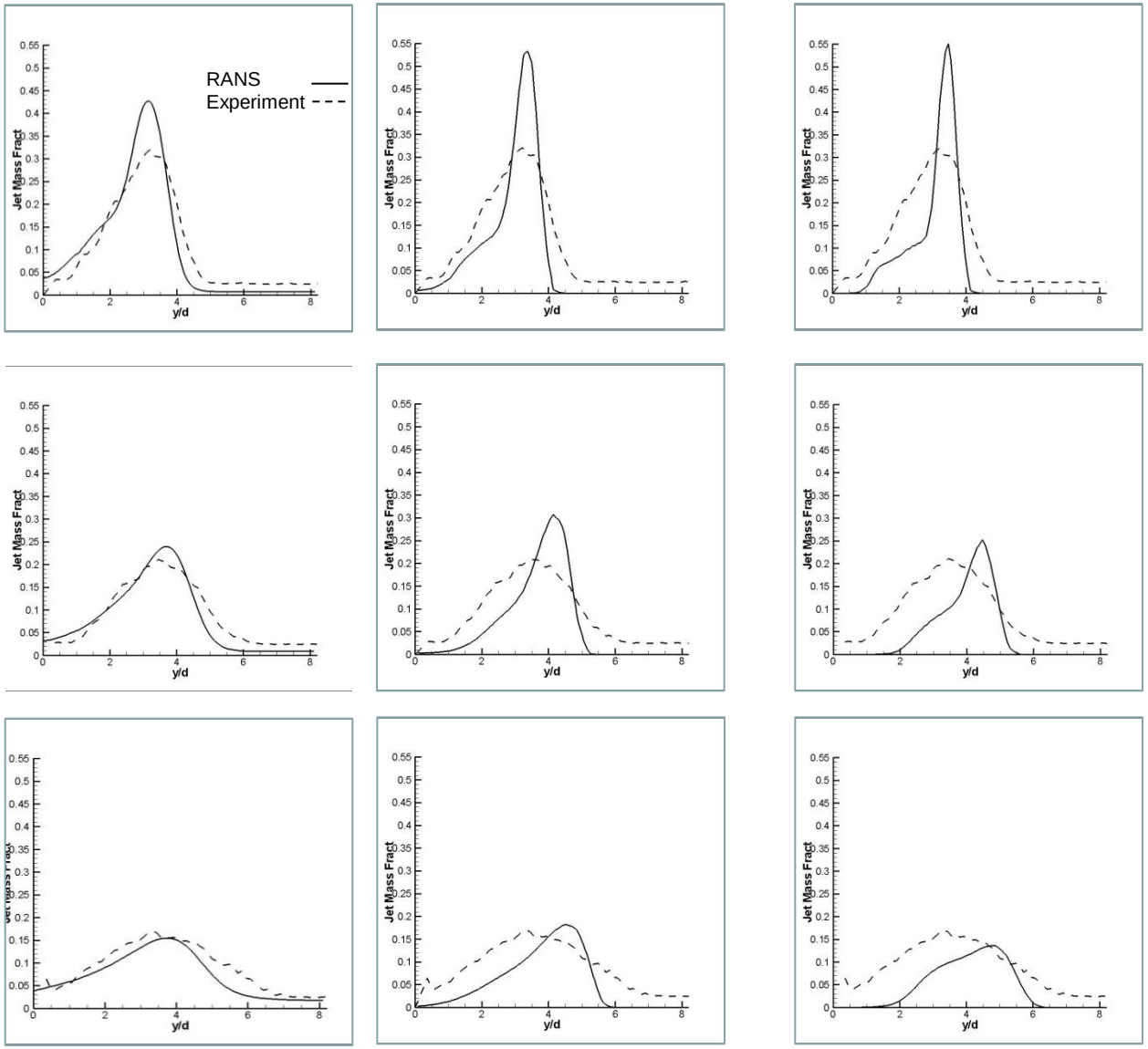
Axial locations (d = inj. dia.)

X = 2d:

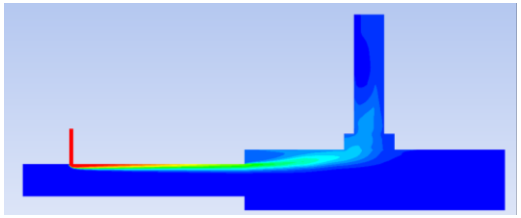
X = 5d:

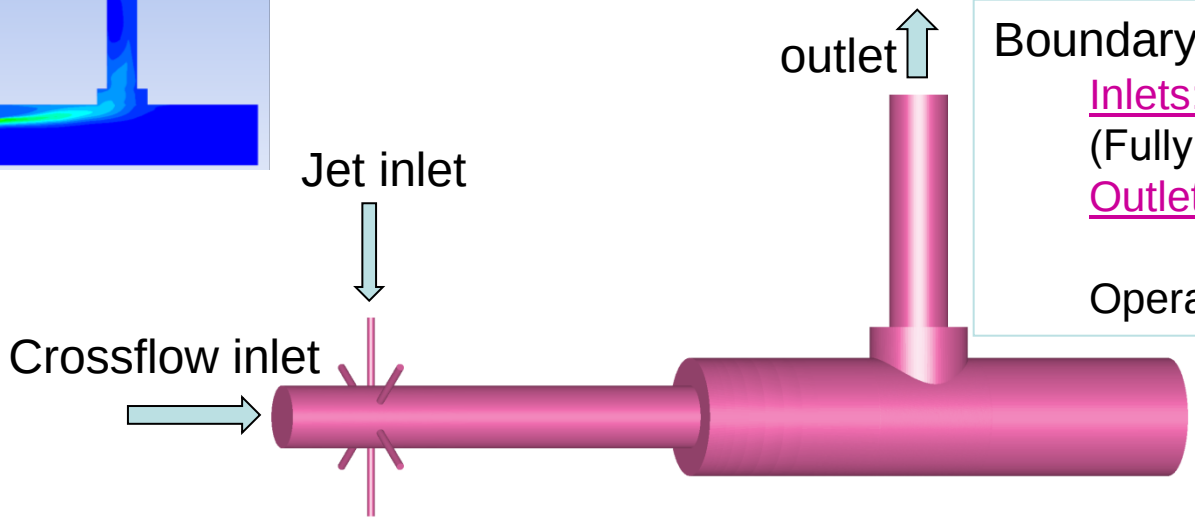
X = 10d:

Fluent | STAR-CCM+ | CFD++



AFRL Water-to-Water Experimental setup



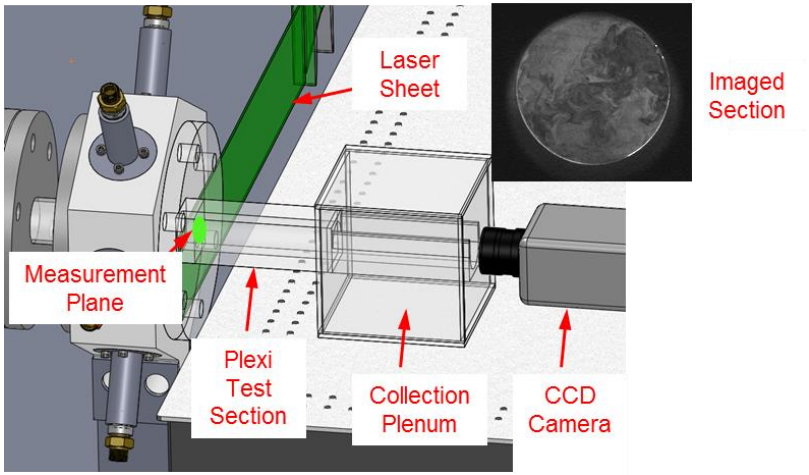


Boundary conditions:

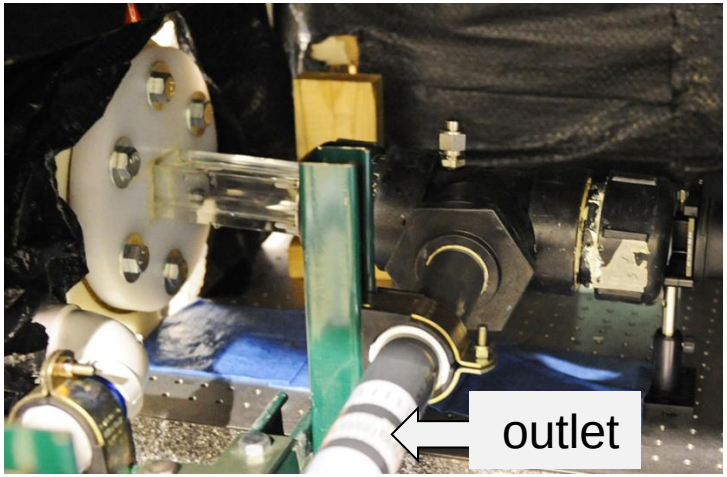
Inlets: Velocities, species, K, (Fully devp'd turb. profiles)

Outlet: Static Pressure, K, ε

Operating liquid: Water



Schematic of the experimental setup

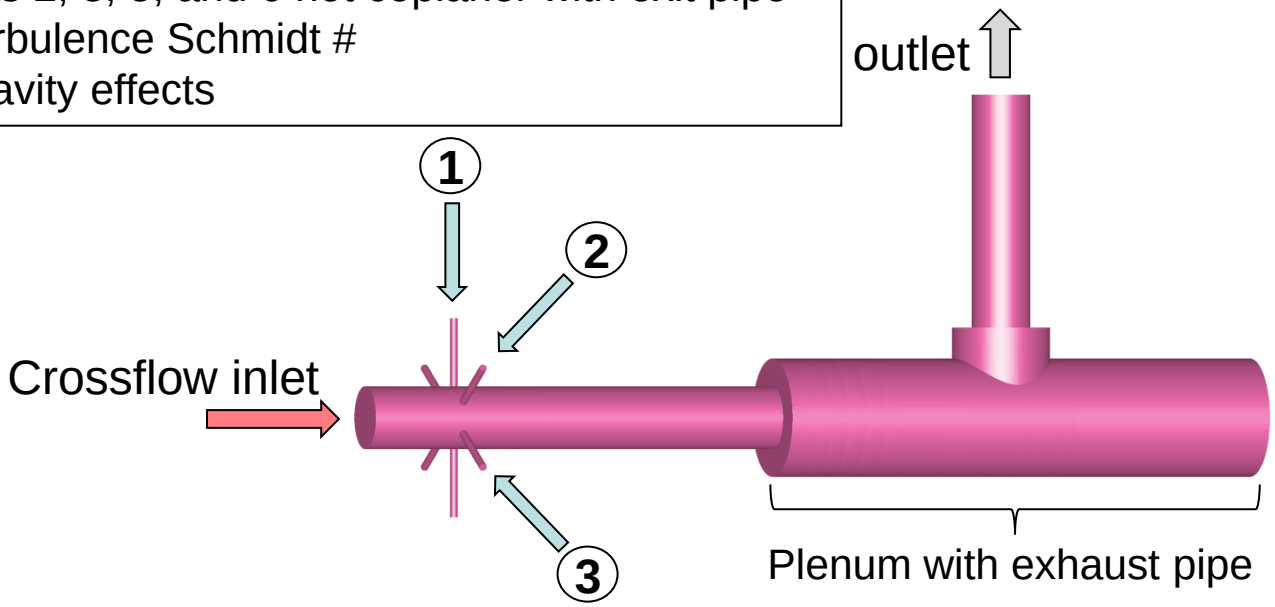


Experimental setup

Simulation matrix

Considerations:

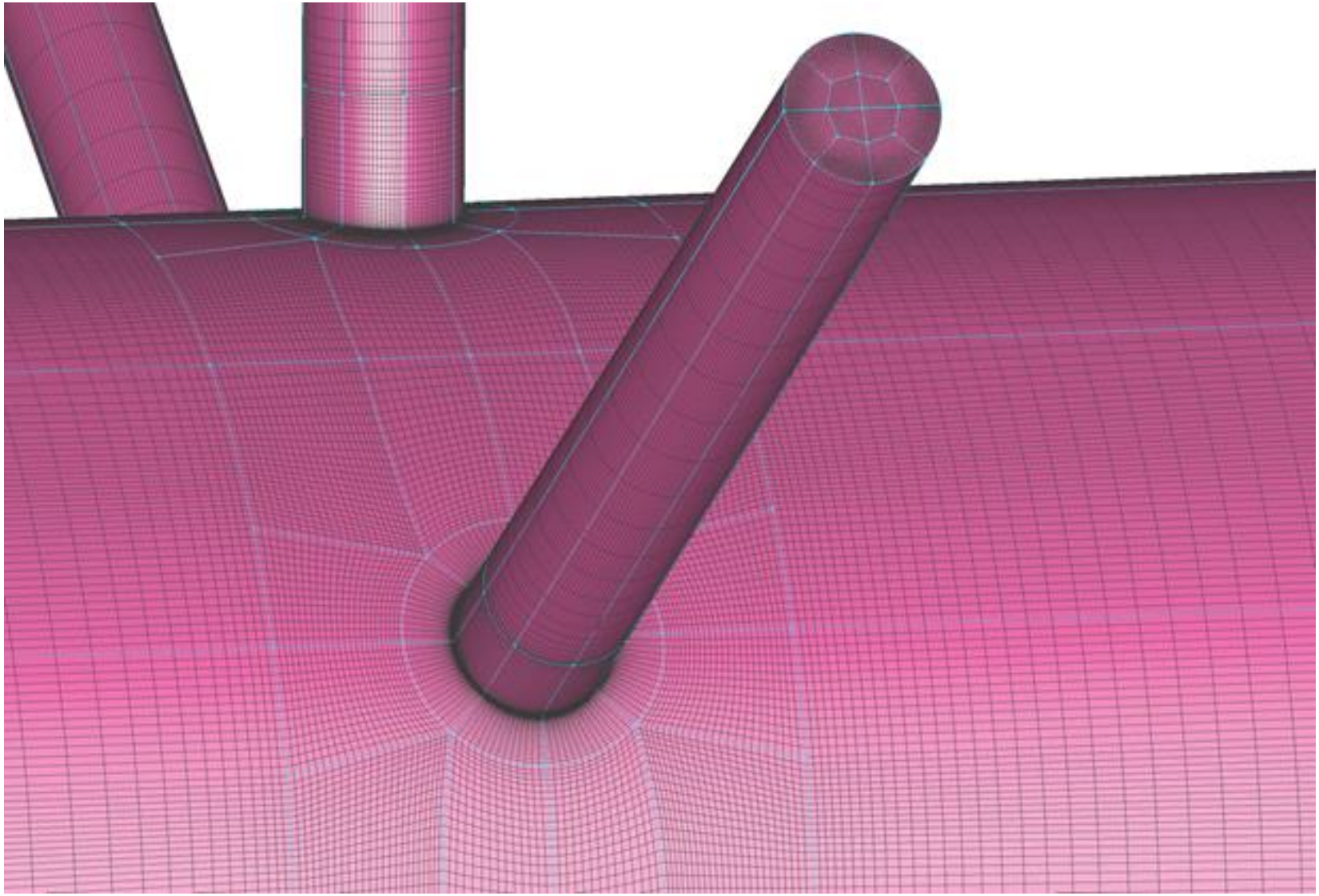
- Turning of outlet Flow
- Jets 2, 3, 5, and 6 not coplaner with exit pipe
- Turbulence Schmidt #
- Gravity effects



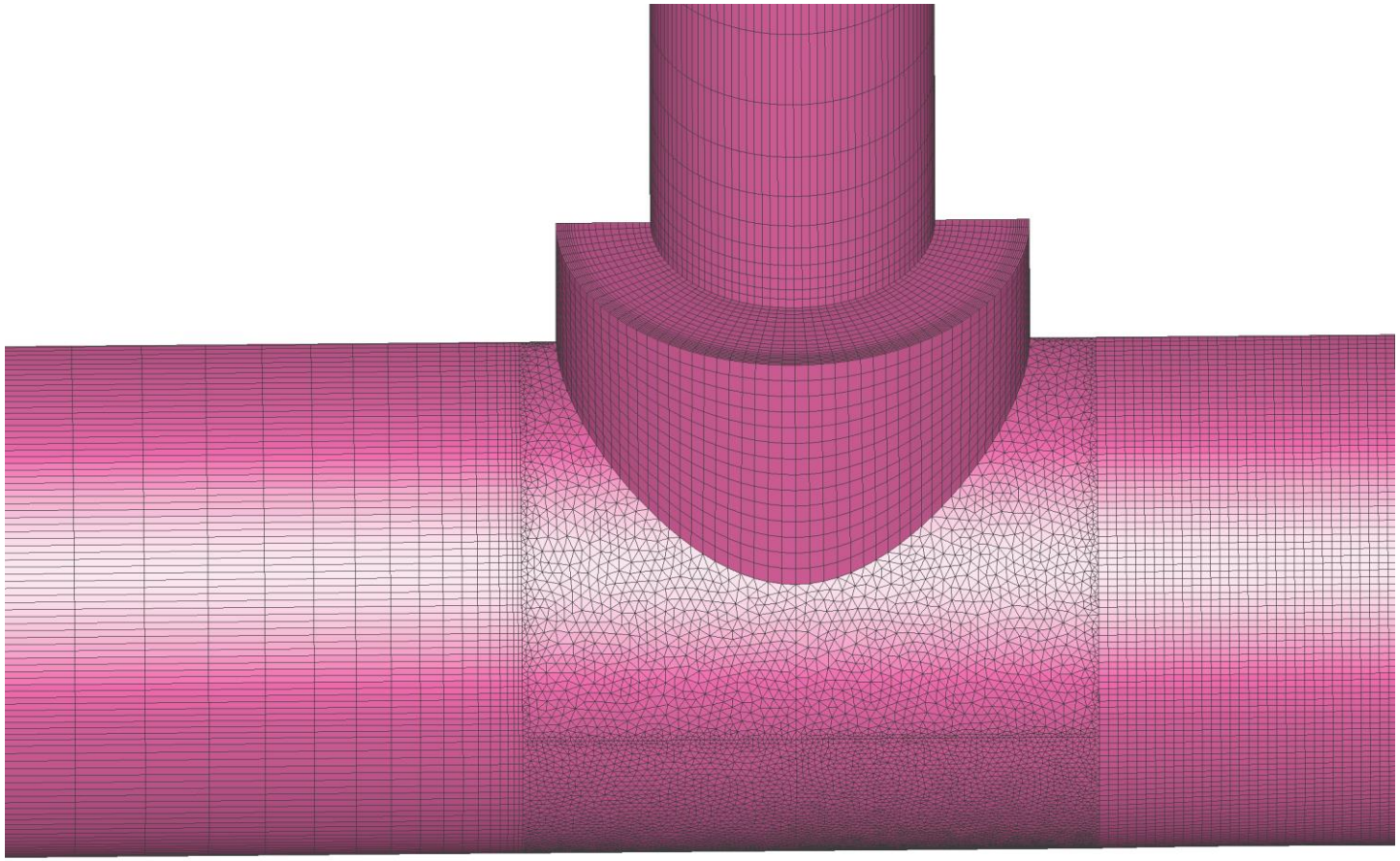
- Simulation Matrix:
  - Single injector without plenum outlet
    - Smaller computational domain, less computational resources needed
  - Single jet + plenum
  - Multiple jets: 2, 4, 6
  - Momentum flux ratios: 3.2, 8.2, 14.3, 20.3, 28.3, 36.5, 47.3

Grid Distribution Around the Jet

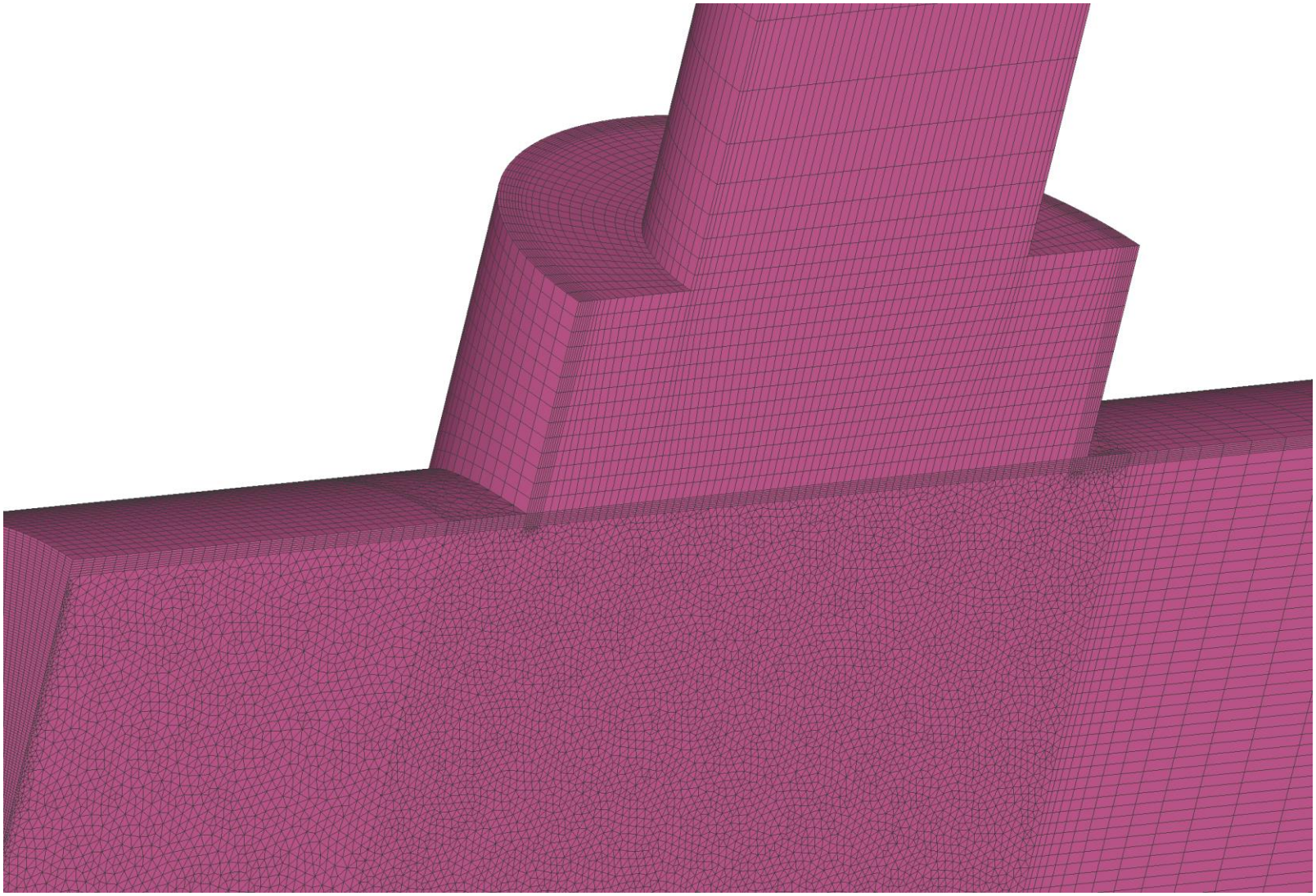
(Total cells: 3 million Hex Cells)



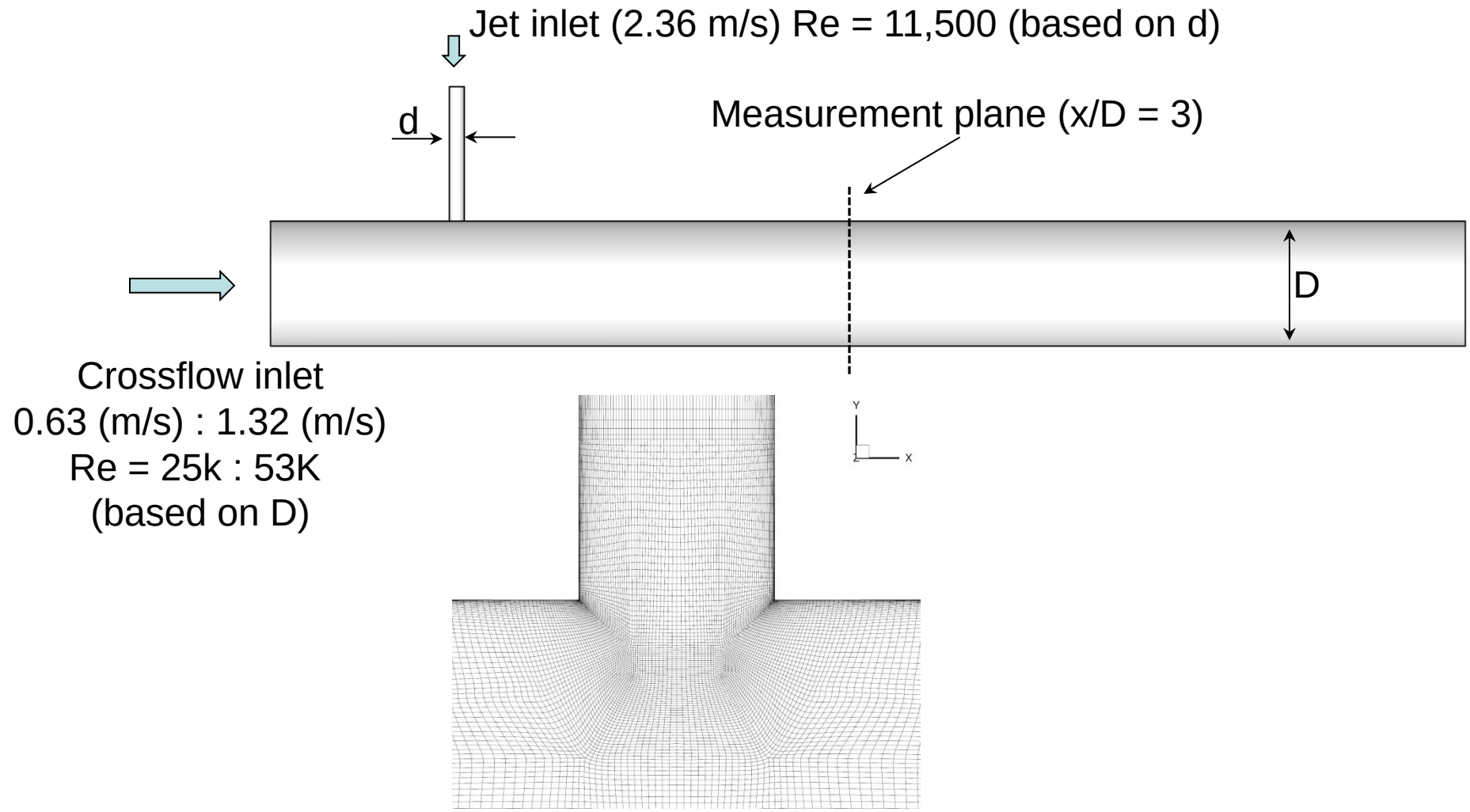
Grid Distribution Around the Outlet (Total cells: 3 million Hex Cells)



Hybrid Grid Around the Outlet:



Geometry for the Single jet without the Outlet Plenum



Grid at the jet area (Overall :2.2 million hex cells)

Computational setup and Solution Procedure

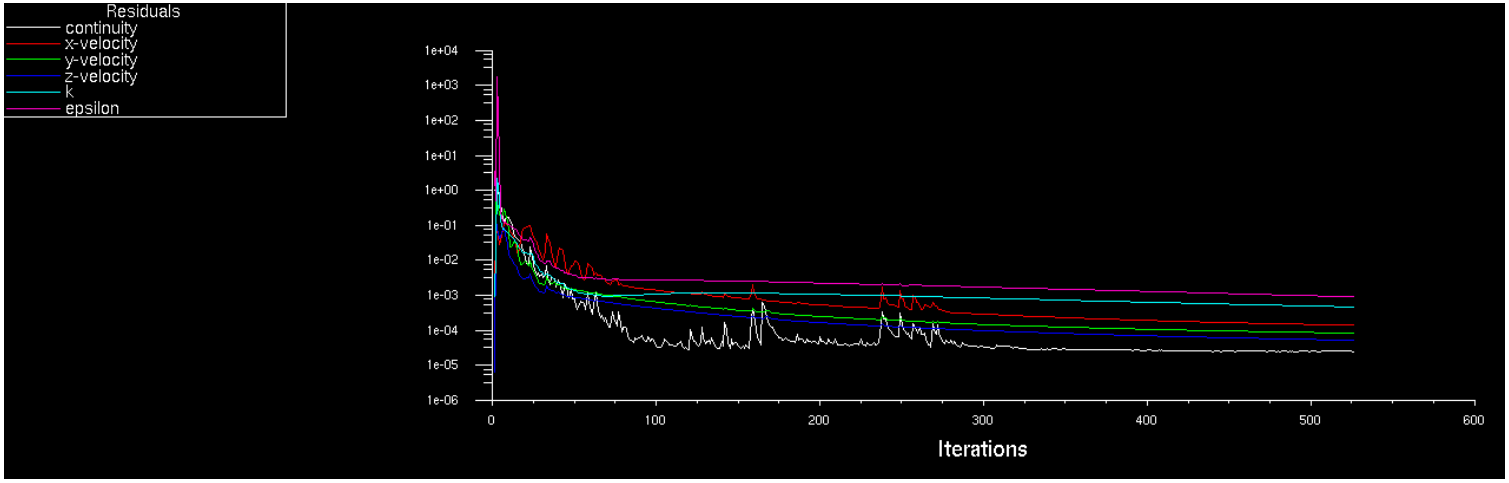
- **Equations Solved:**
  - Momentum Eqs.
  - Continuity
  - Turbulent Kinetic Energy (TKE)
  - Turbulent Dissipation Rate (TDR)
  - Species
- **Boundary Conditions:**
  - *Inlet BCs*: Velocities, K, ε
    - Inlet BCs are inlet profiles obtained from separate fully developed pipe flow simulations
  - *Exit BC*: Static Pressure
- **Discretization:** Second Order Upwind for all the equations
- **Turbulence Model:** Low Reynolds number K-ε (K-ω, and other variants of K-ε with various options were also tried)
- **Material Type:** Liquid water

Computational setup and Solution Procedure

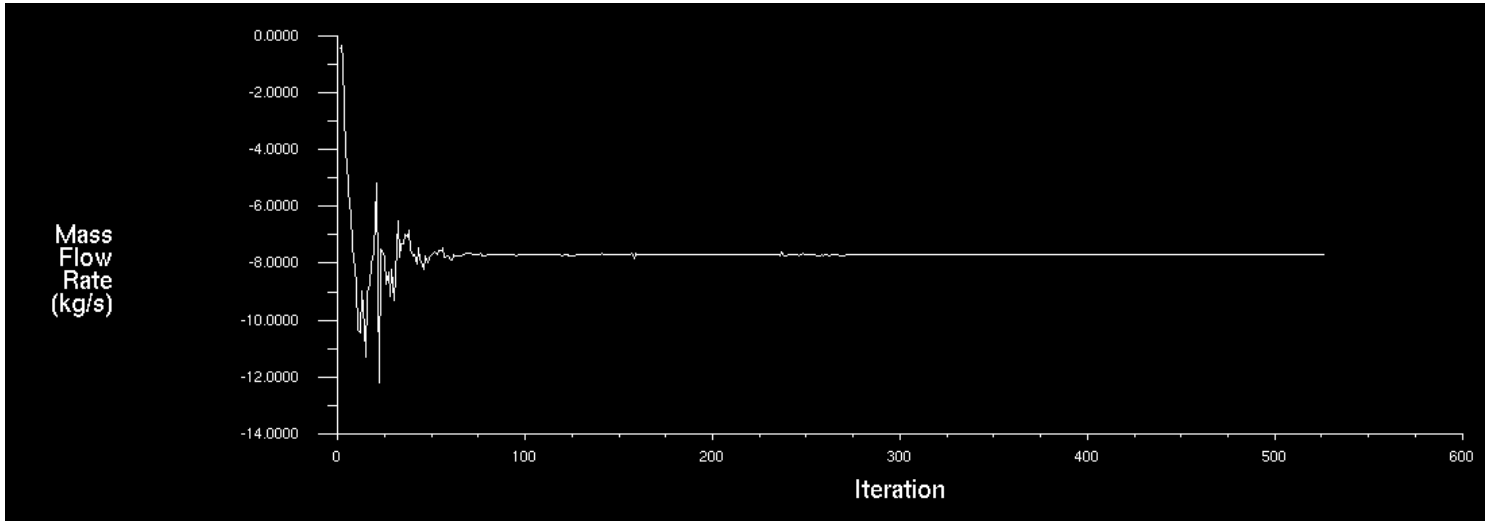
. . . Continued

- **Number of Grid Points:**
  - Simulation performed on one half of the geometry utilizing the gemoetry symmetry
  - Two grids generated:
    - Single jet without plenum: 2.2 million all hex cells
    - Single jet with plenum: 3 million mostly hex cells
    - Wall $y^+ < 1$
  - Fine grids allowed use of the low Reynolds number K-ε turbulence model integrating the solution to the wall

Solution Convergence History

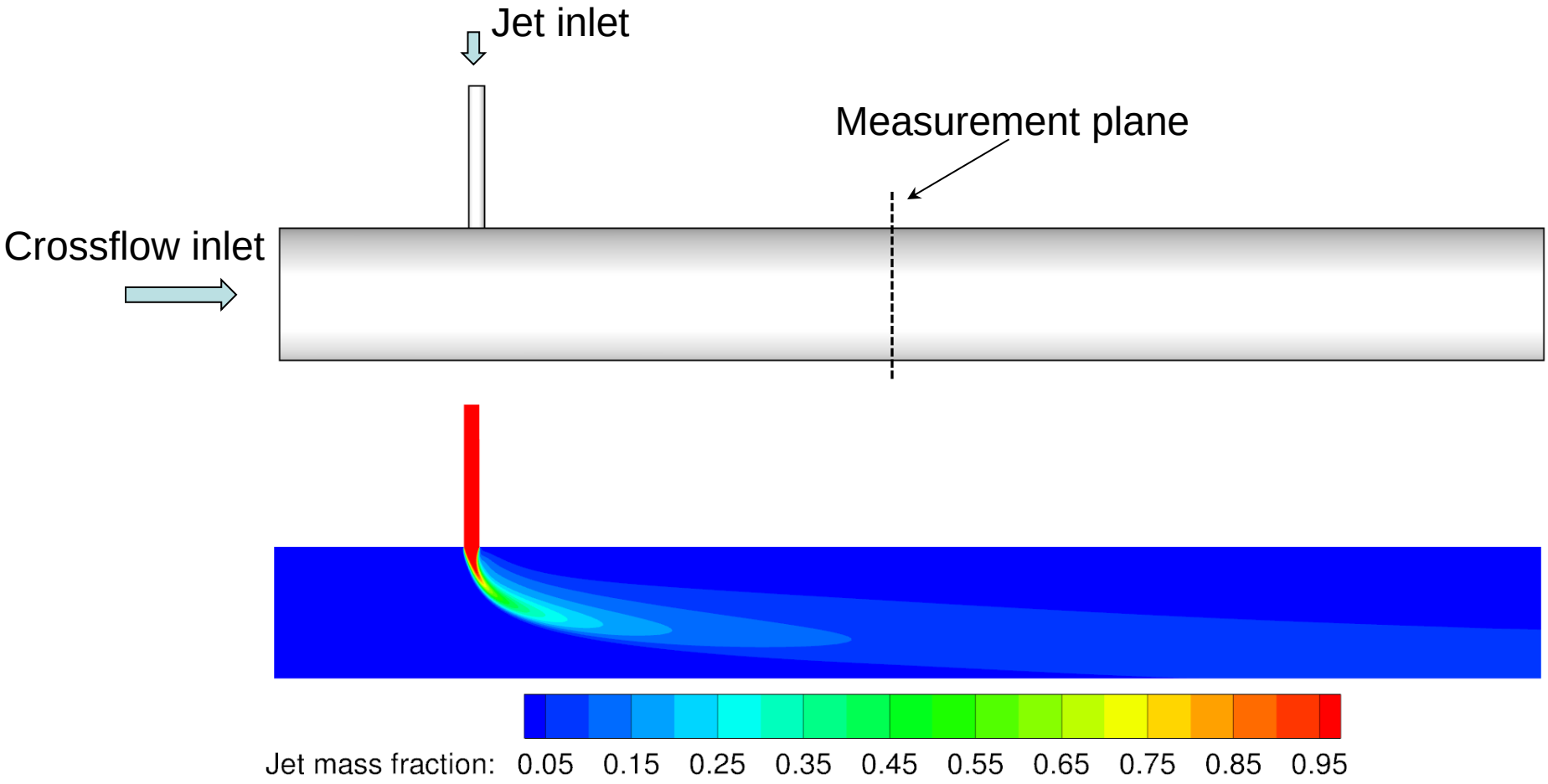


Convergence History of Equations' Residuals



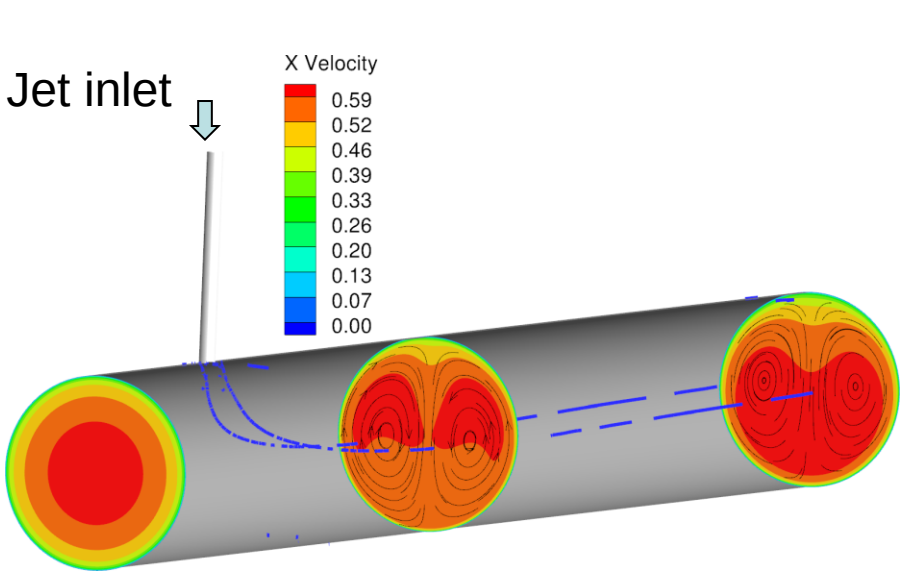
Convergence History of Mass Flow Rate at the Exit

Geometry for the Single jet without Outlet Plenum

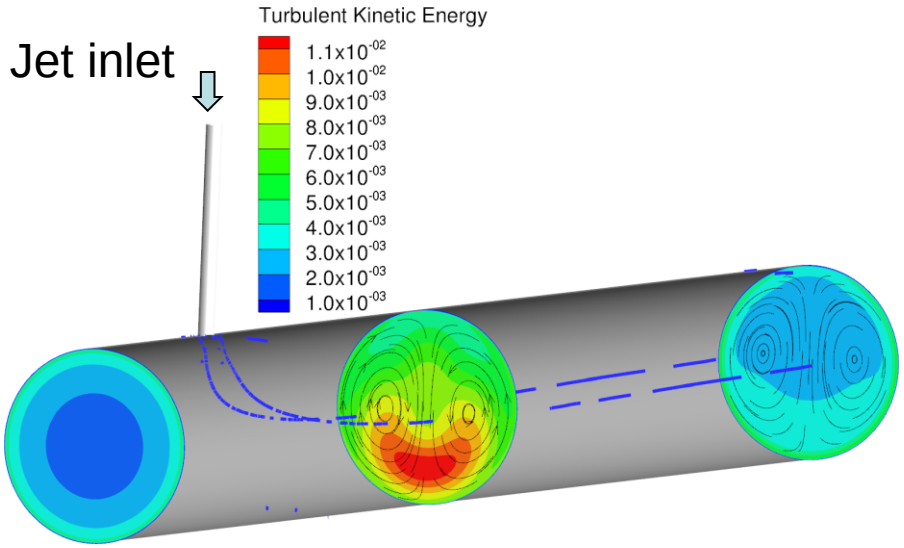


Jet mass fraction, J = 14.3

Axial Velocity & TKE at: Inlet, Measurement Plane, and at Exit (J = 20.3)



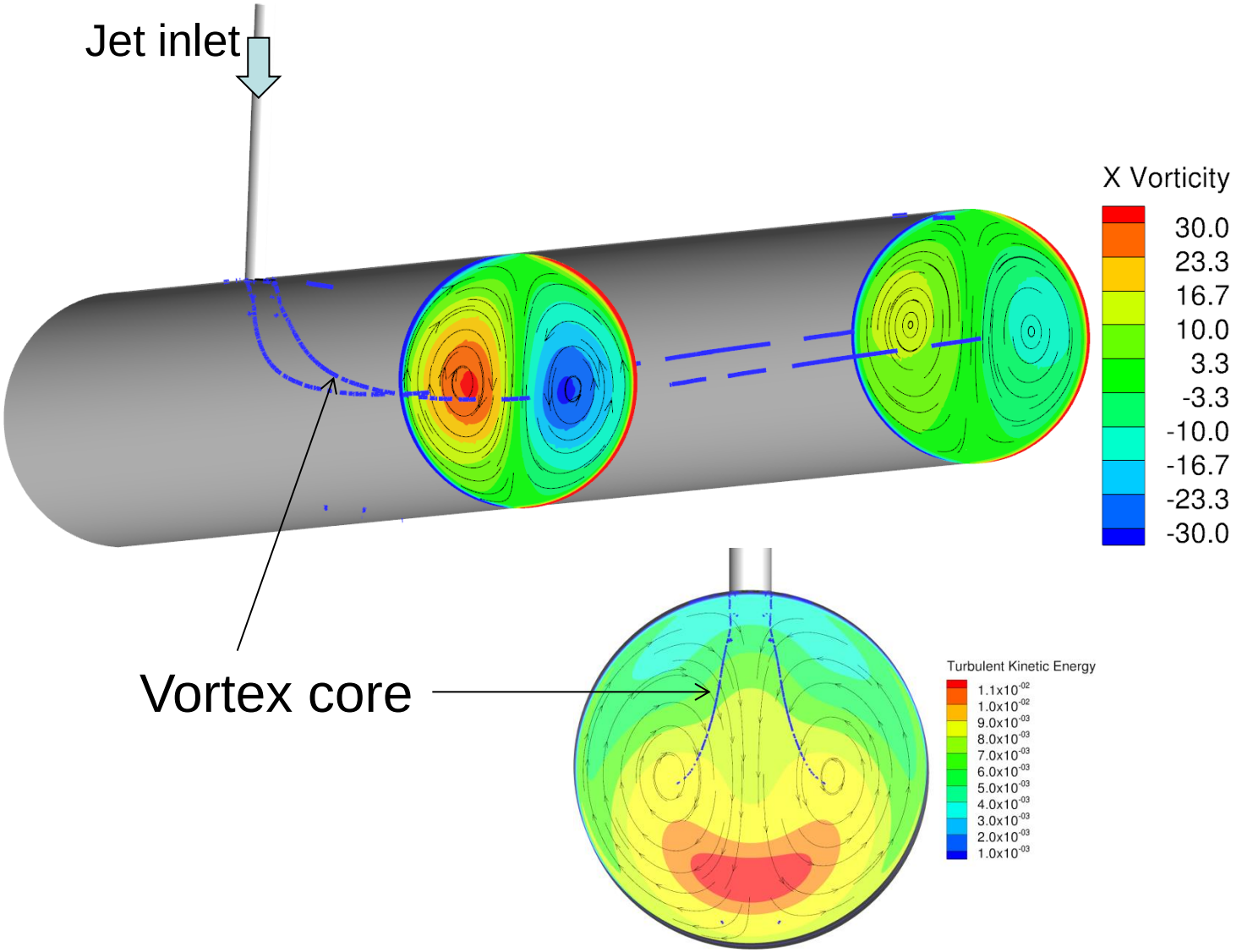
Axial velocity



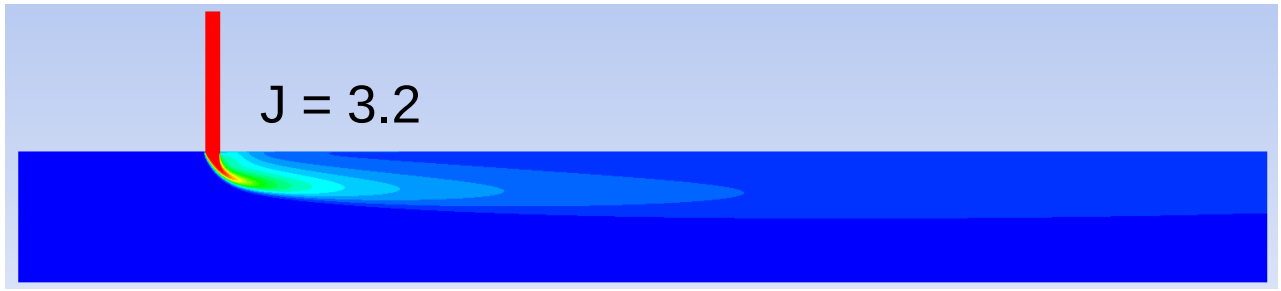
Turbulent Kinetic Energy

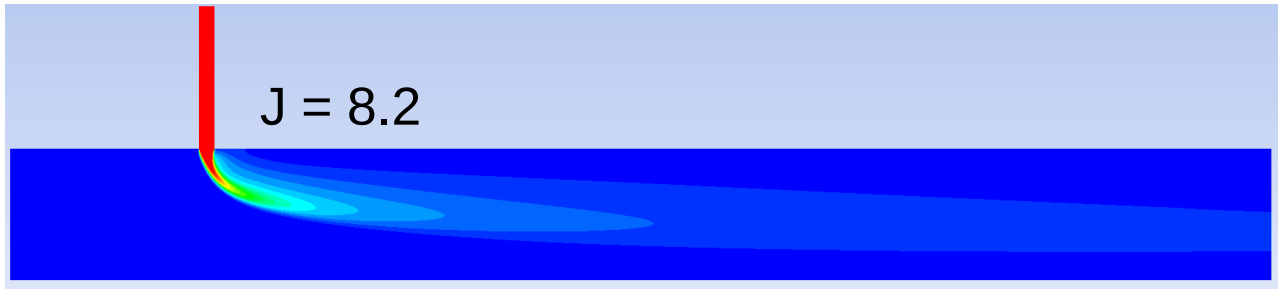
Note the Fully Developed Turbulent Inlet Profile

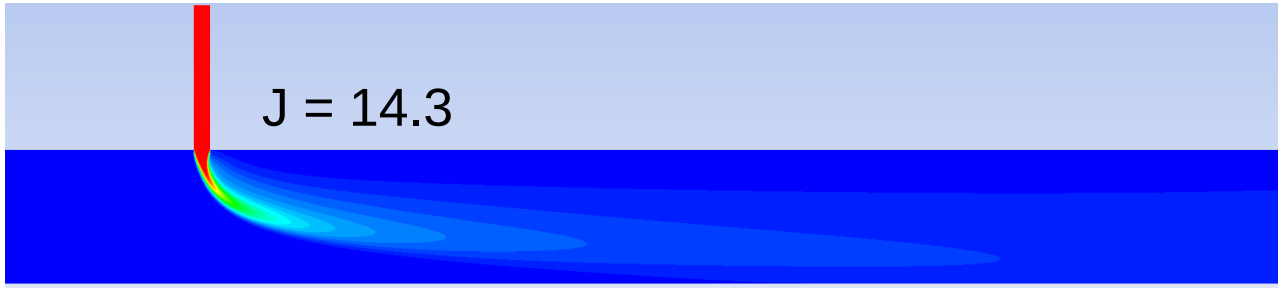
Vortex Core and X-component of Vorticity Distributions at the Measurement Plane and at Exit Plane (J = 20.3)

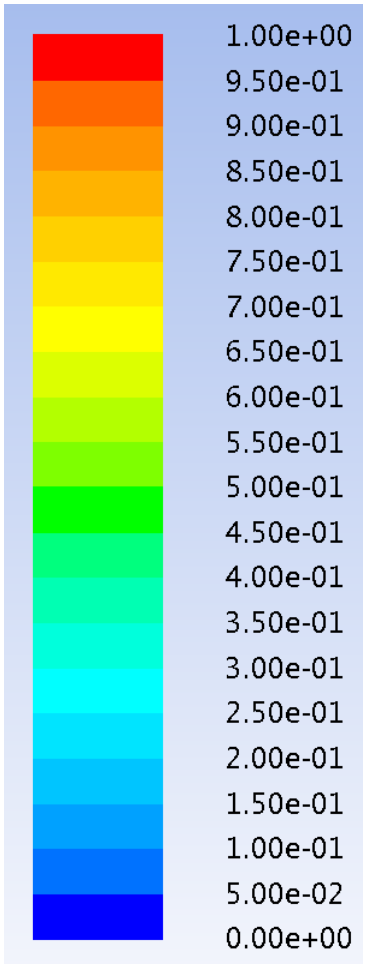


Jet Mass Fraction Distributions & Penetration for Different Momentum Flux Ratios (J) Continued . . .

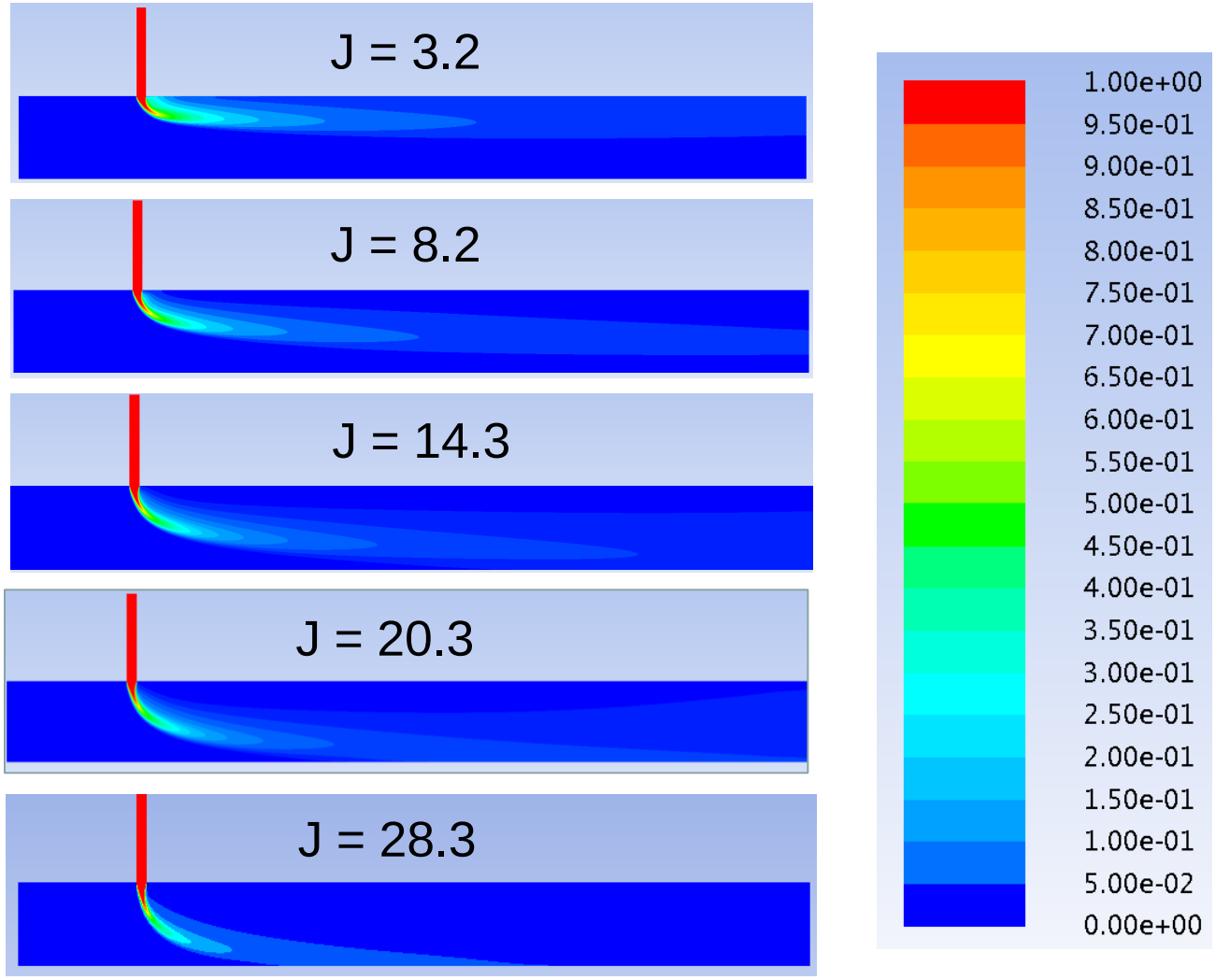






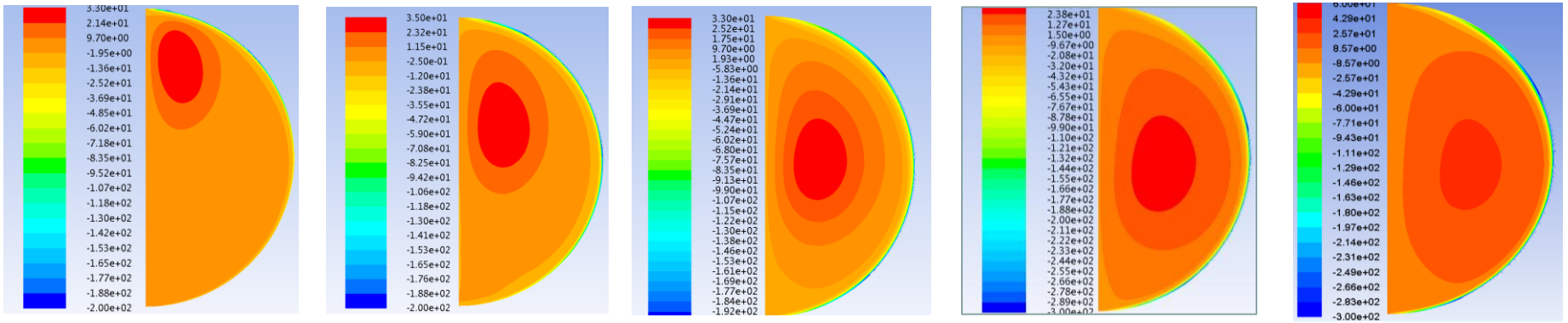


Jet Mass Fraction Distributions & Penetration for Different Momentum Flux Ratios (J)

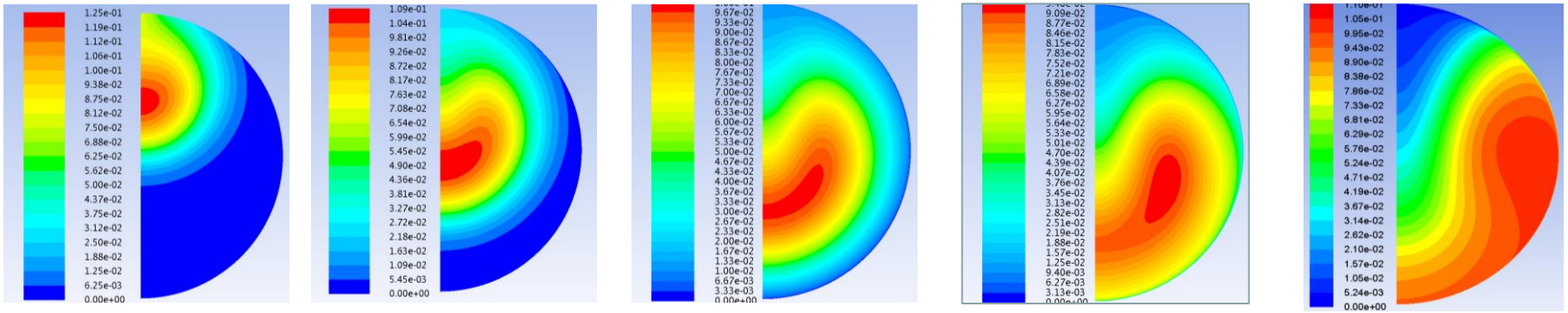


Computed X-vorticity & Jet Mass Fraction Distributions at the x/D = 3

J = 3.2 J = 8.2 J = 14.3 J = 20.3 J = 28.3



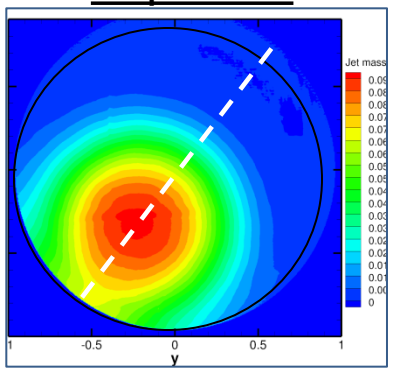
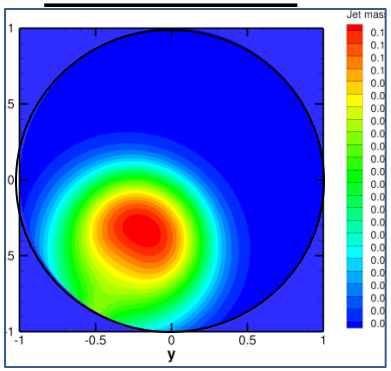
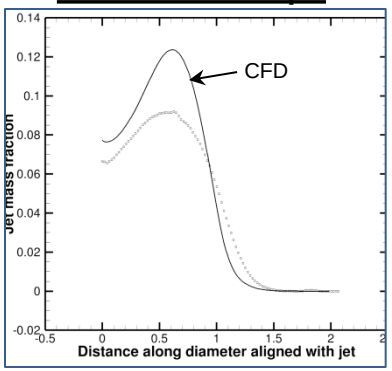
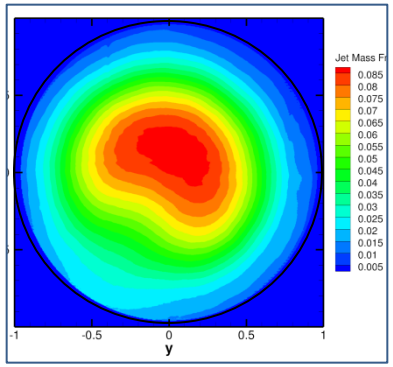
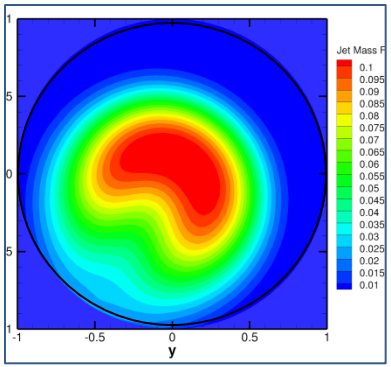
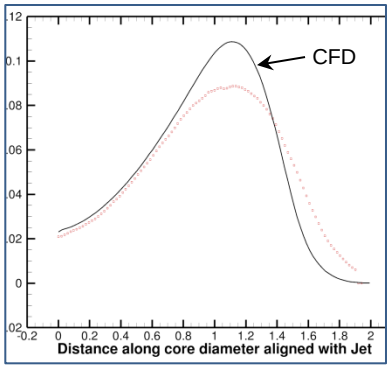
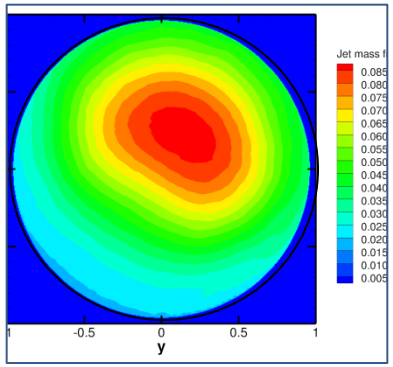
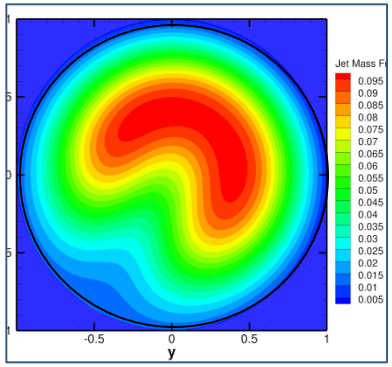
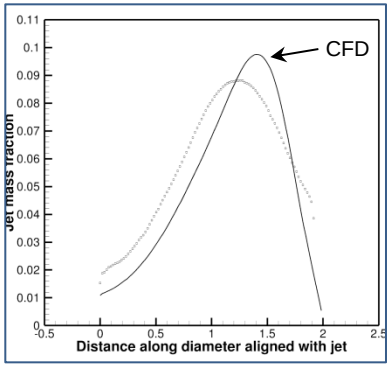
X-vorticity



Jet mass fraction

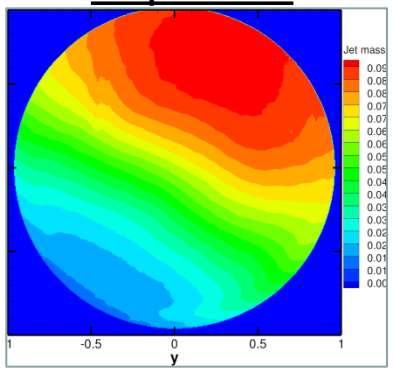
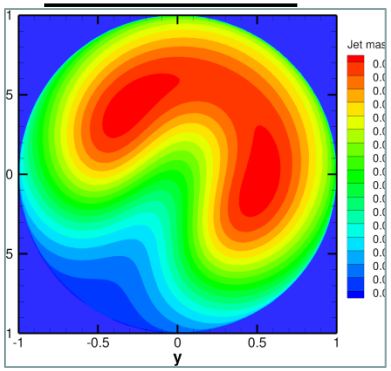
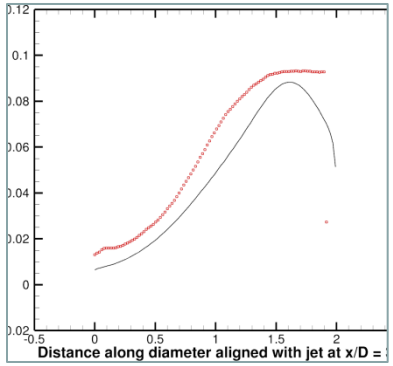
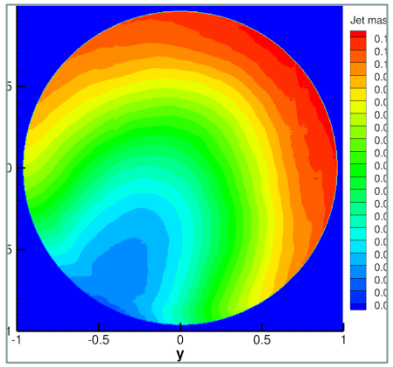
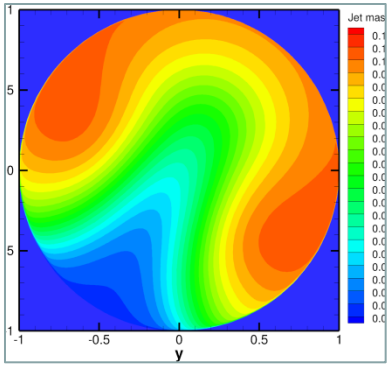
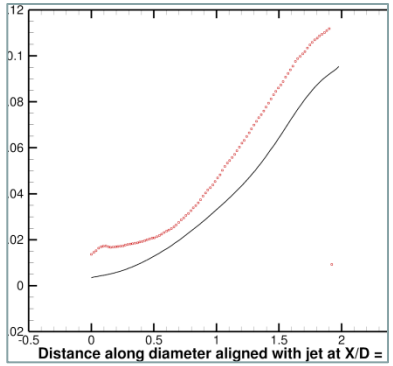
Computed and Measured Jet Mass Fractions

Continued . . .

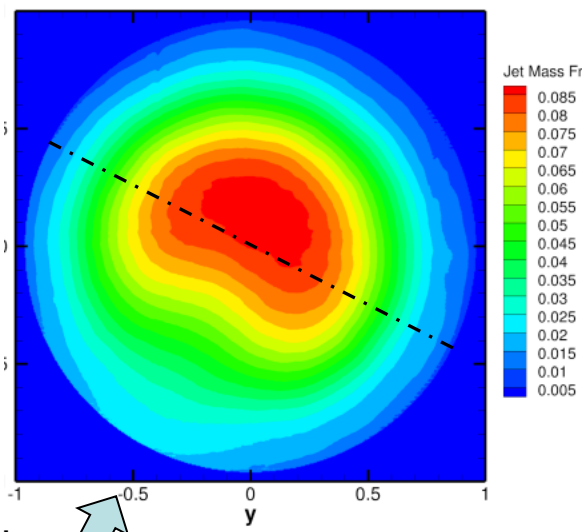
Momentum flux ratio	Exp. data	CFD results	CFD vs Exp.
3.2:			
8.2:			
14.3:			

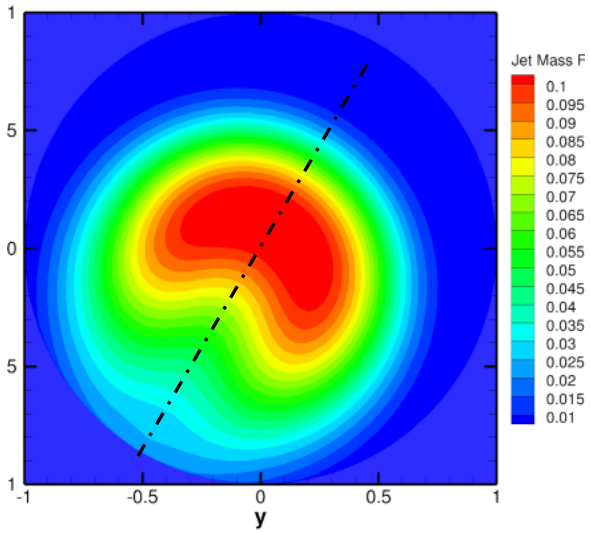
Jet

Computed and Measured Jet Mass Fractions

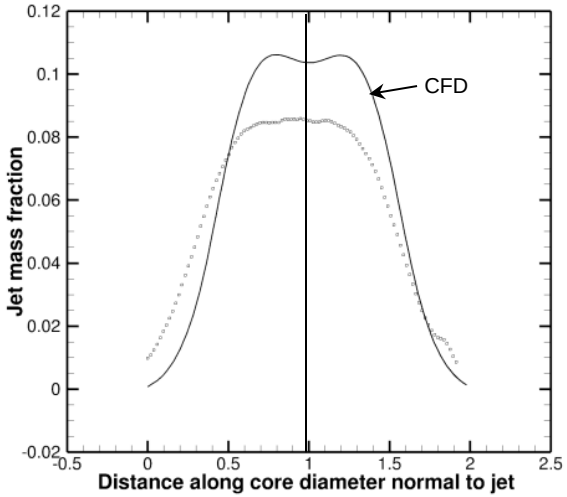
Momentum flux ratio	Exp. data	CFD results	CFD vs Exp.
20.3:			
28.3:			

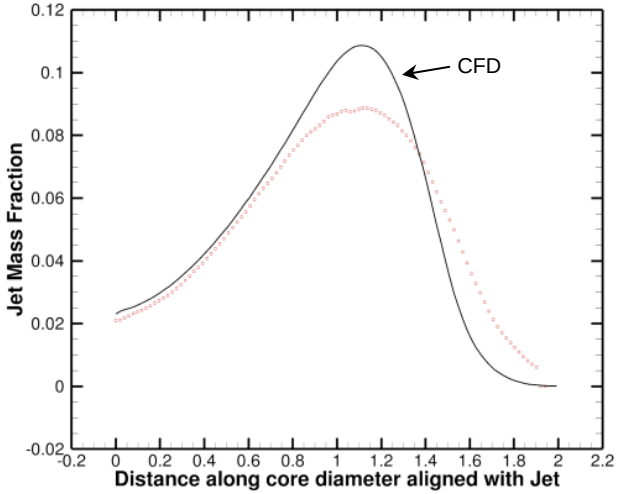
Computed and Measured Jet Mass Fractions (Momentum Flux Ratio = 8.2)



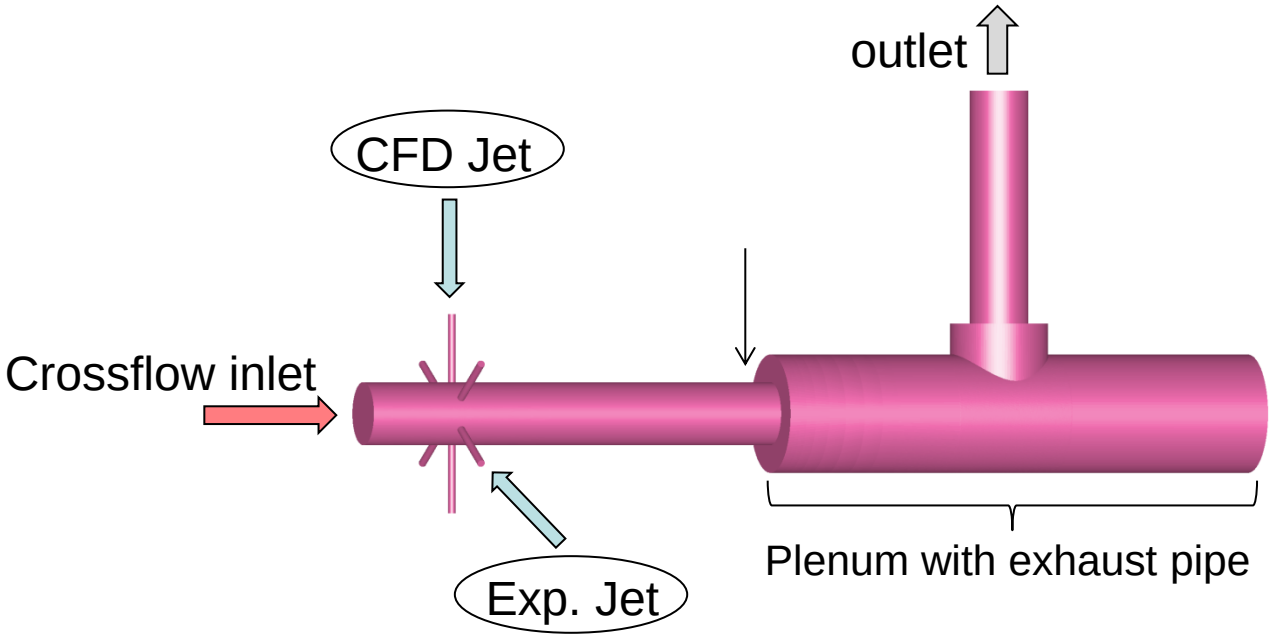


Jet direction





Computational & Experimental Jets



- Turbulence Schmidt number
- Computational domain does not include the plenum and the exhaust pipe
- Experimental Jet is not coplanar with exit pipe
- Fluid issuing through experimental jet has to rotate & turn to exit
- Fluid issuing through computational jet has to only turn to exit

Summary & Future Work

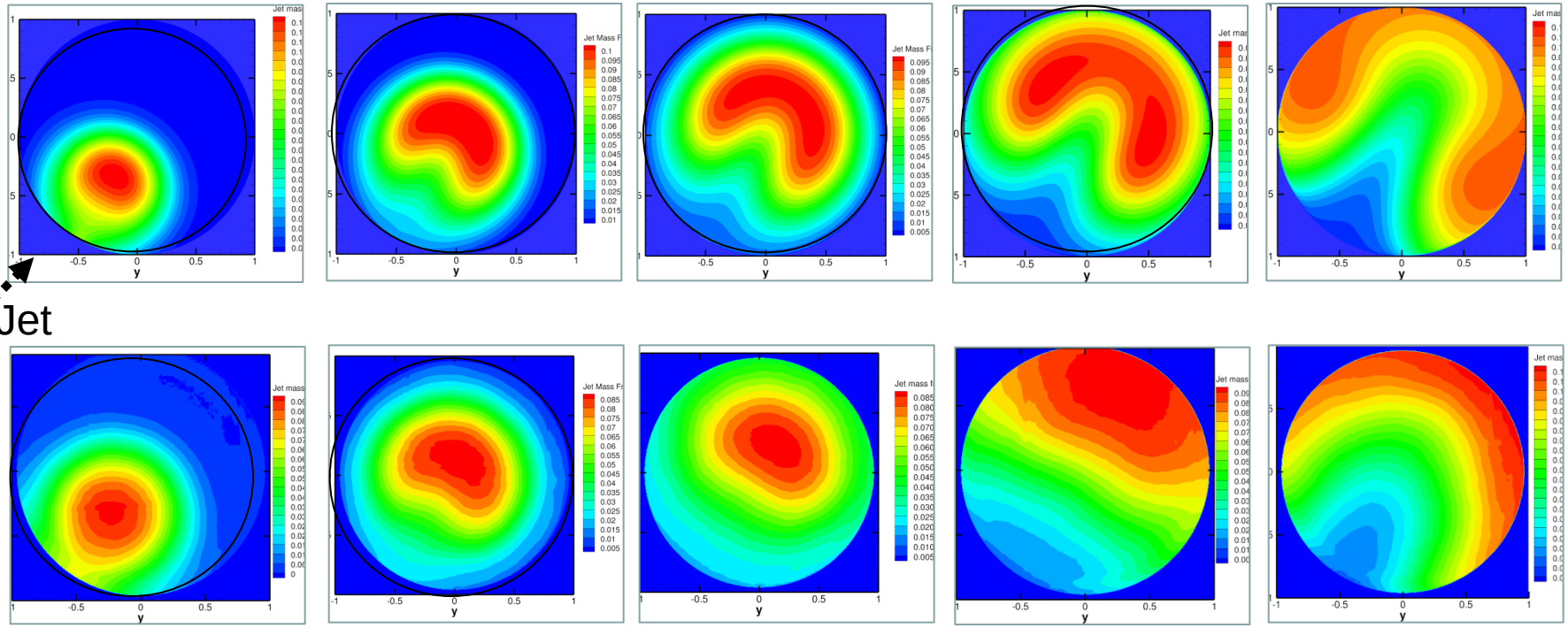
- A series of experiments and RANS simulations are performed to investigate JICF induced-mixing for an iso-density liquid (water).
- RANS simulations, using Fluent, captures the flow features such as the CRVs, and show reasonable predictions with the measured concentration data.
- Experimental data shows asymmetry in the wake
- Extensive computations planned:
  - Various momentum flux ratios
  - Multiple jets (2, 4, 6)
  - Plenum effect
  - Turbulent Schmidt number

Computed and Measured Jet Mass Fractions

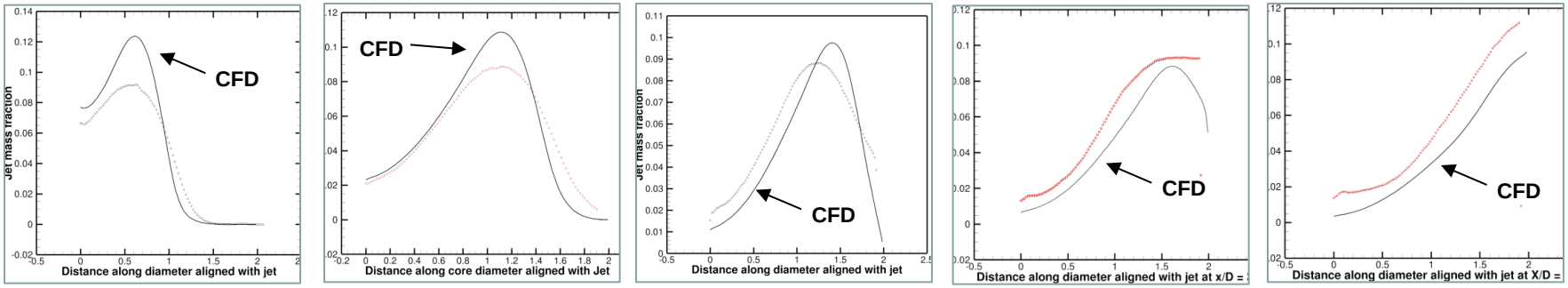
CFD

Jet

EXP

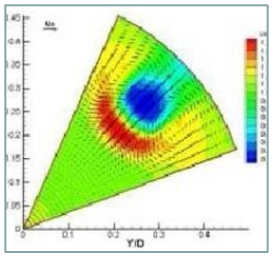
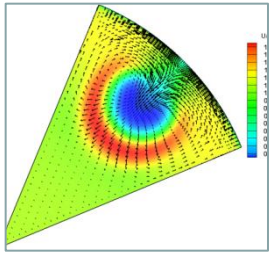
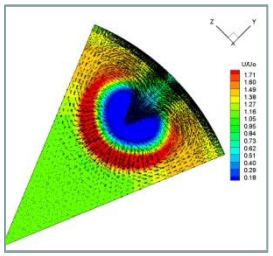
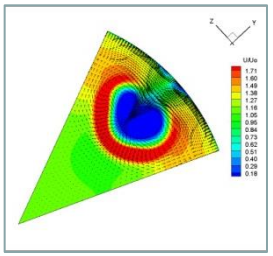
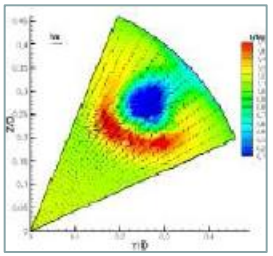
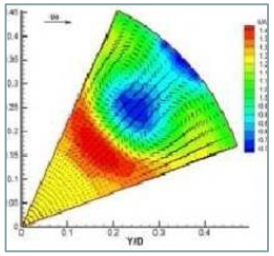
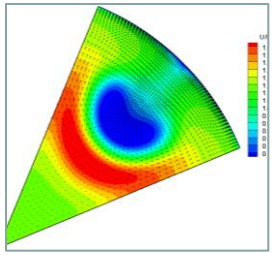
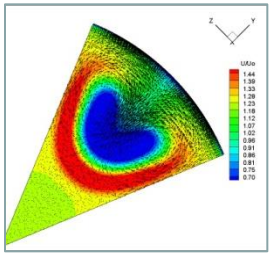
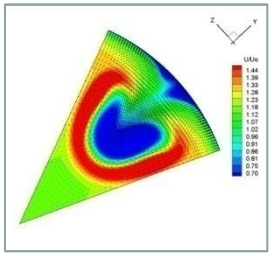
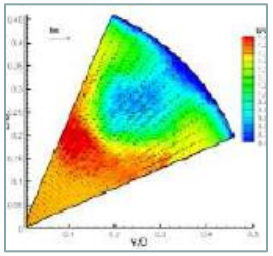
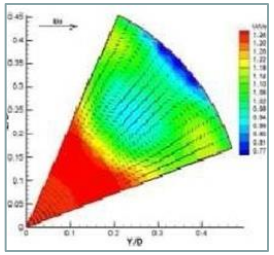
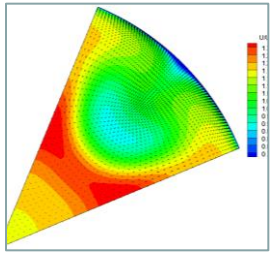
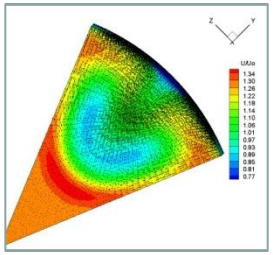
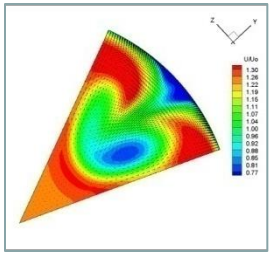
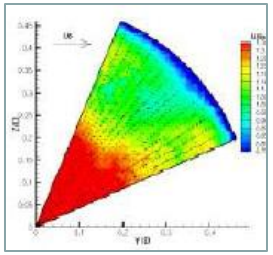


J = 3.2 J = 8.2 J = 14.3 J = 20.3 J = 28.3



Experimental data versus computational results: Axial Velocity Contours

Axial locations (d = inj. dia.)

	Experiment	Fluent	STAR-CCM+	CFD^{++}	LES (ONERA)
X = 2d:					
X = 5d:					
X = 10d:					

Experimental data versus computational results: Axial Velocity Profiles

Axial locations (d = inj. dia.)

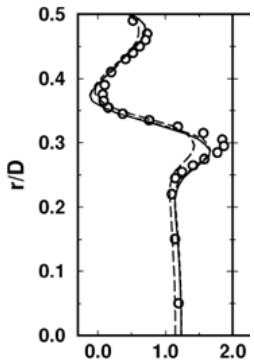
⇩

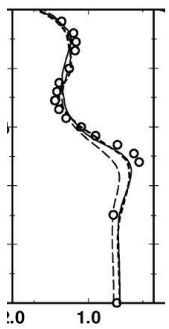
X = 2d:

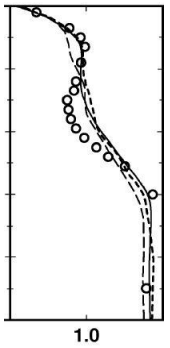
X = 5d:

X = 10d:

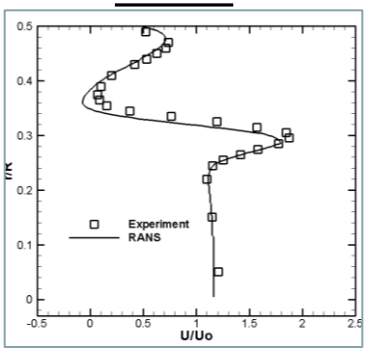
LES (ONERA)

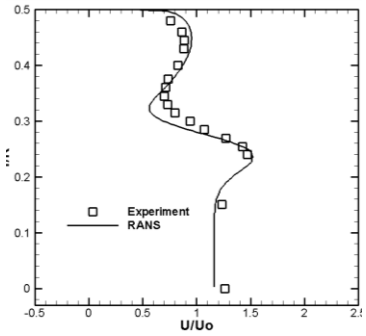


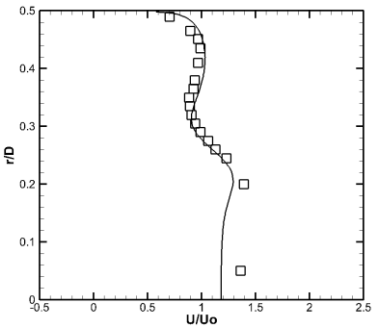




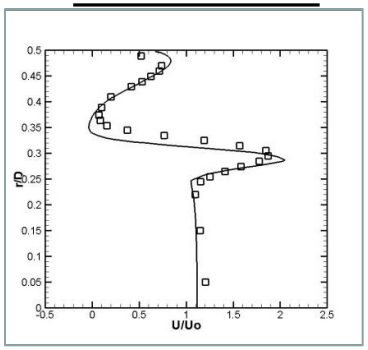
Fluent

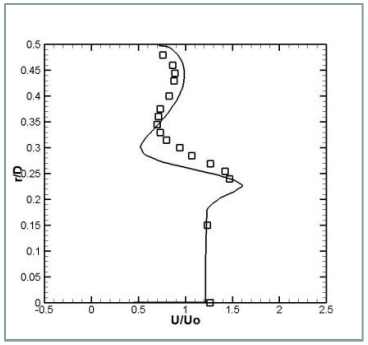


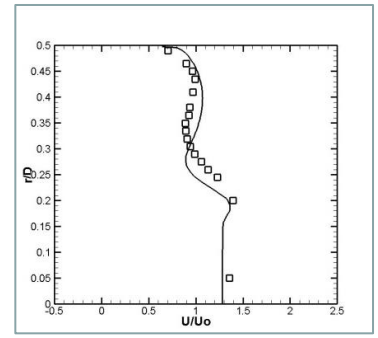




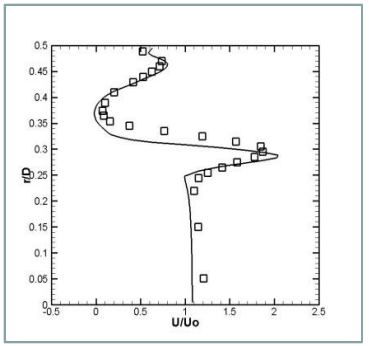
STAR-CCM+

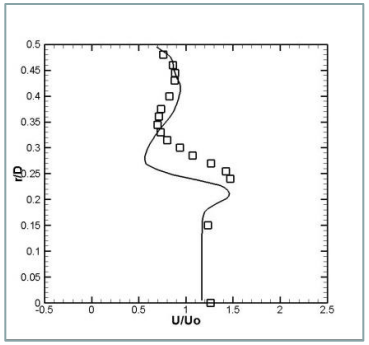


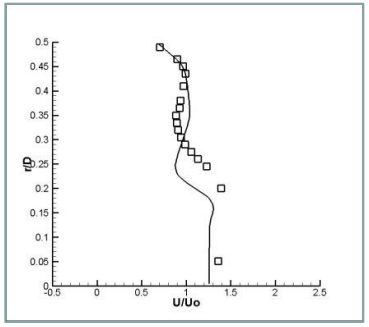




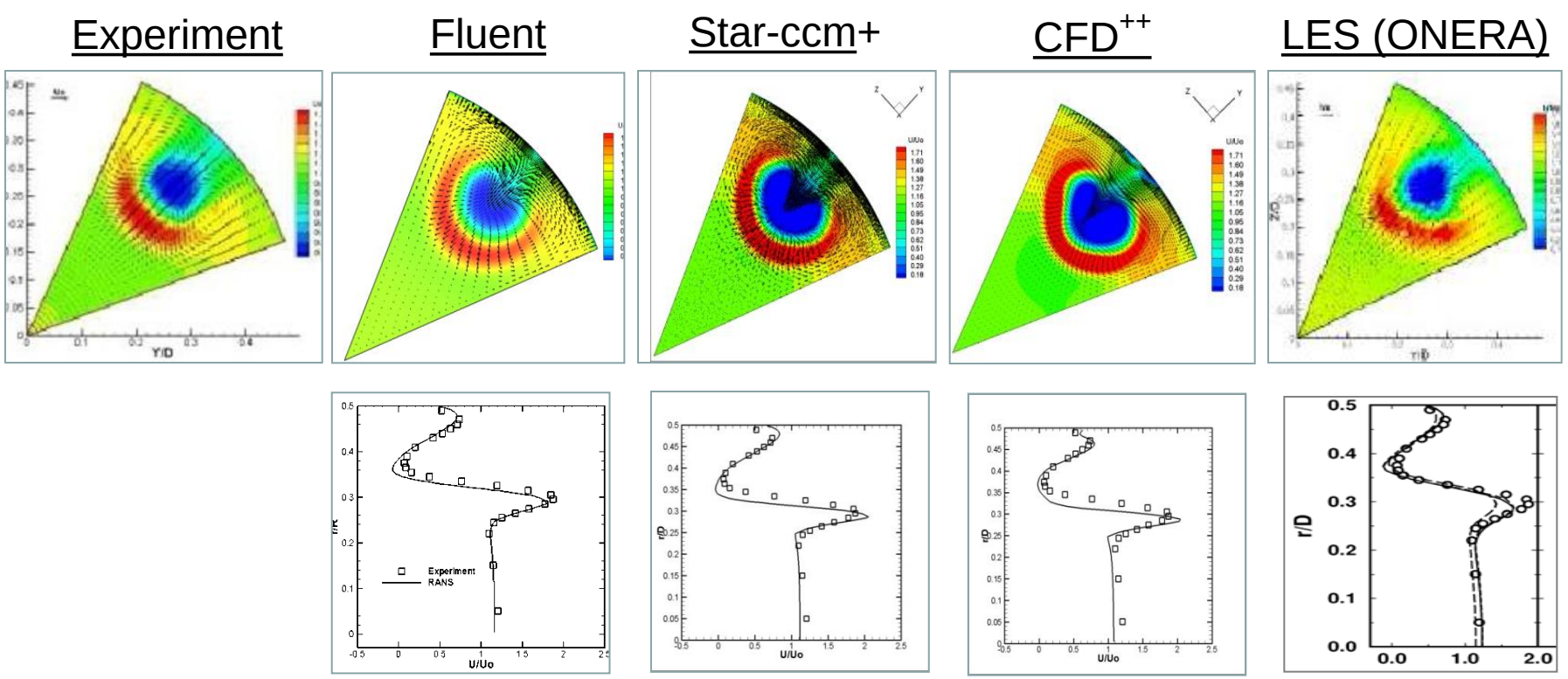
CFD^{++}





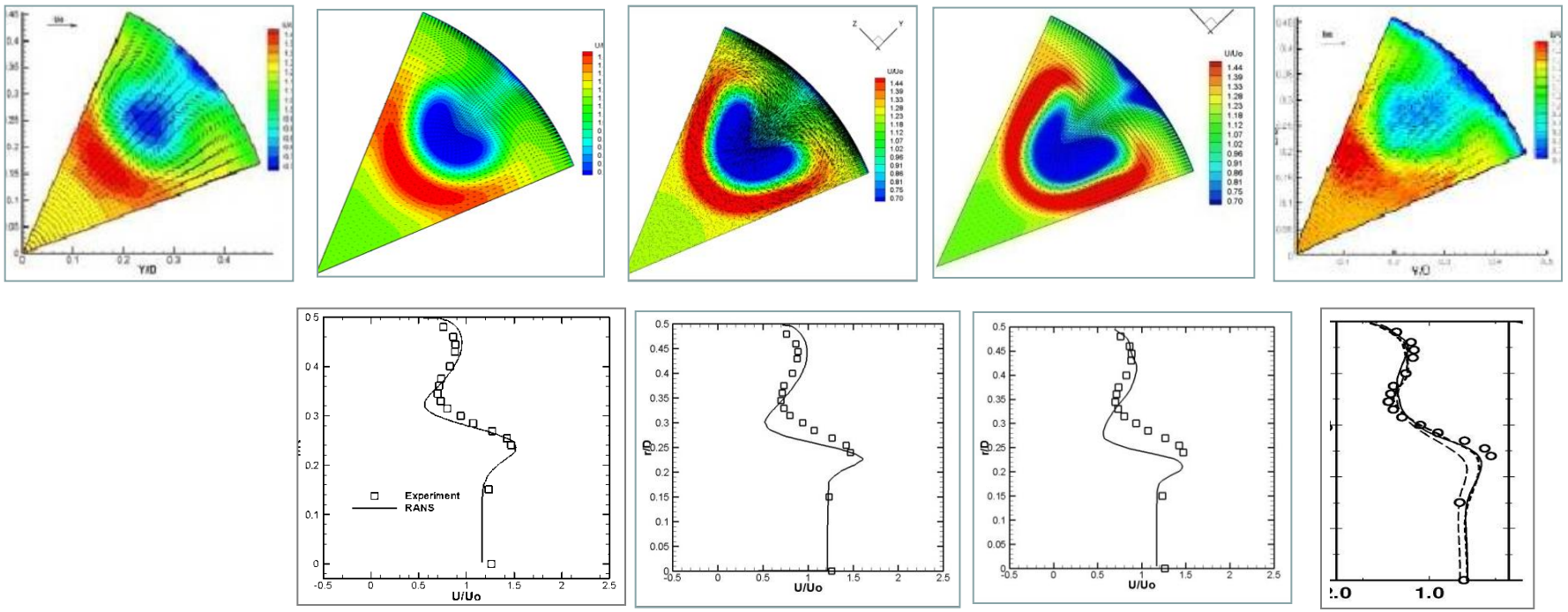


Experimental data versus computational results:



Axial Velocity Contours and Radial Profiles at x = 2d

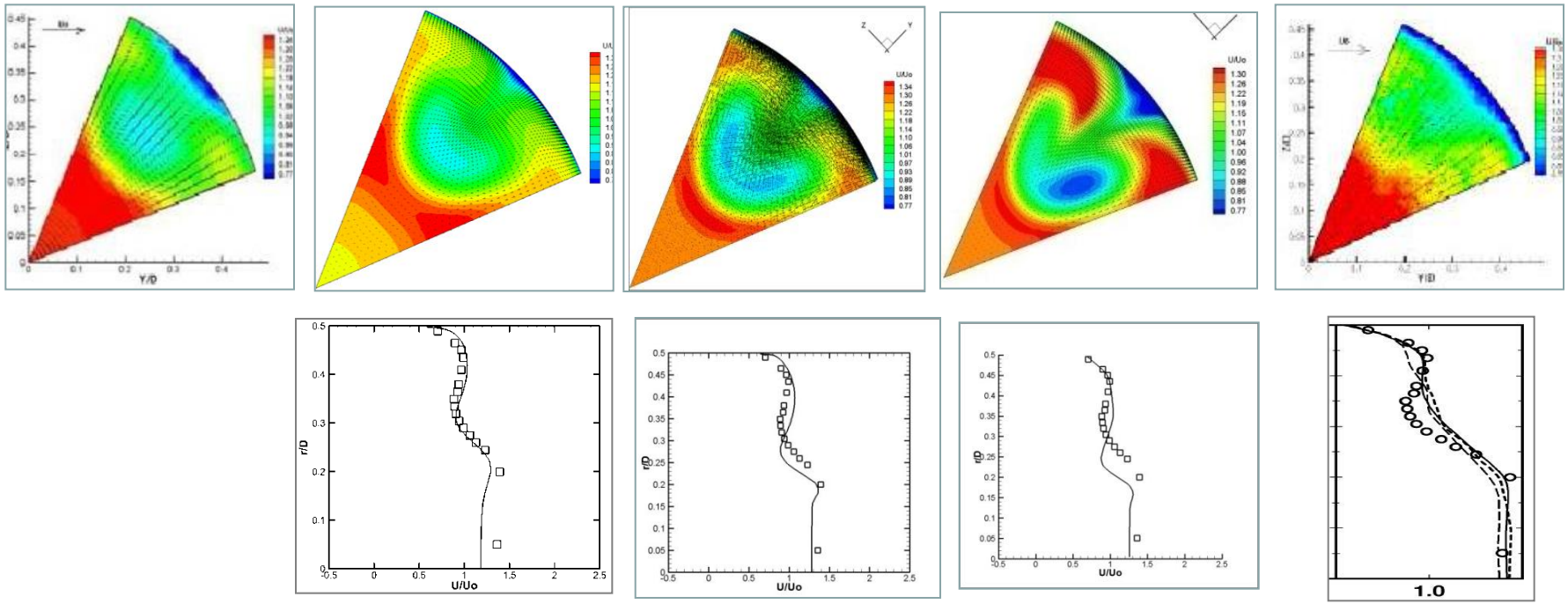
Experimental data versus computational results:



Axial Velocity Contours and Radial Profiles at x = 5d

Experimental data versus computational results:

Experiment | Fluent | Star-ccm+ | CFD++ | LES (ONERA)



Axial Velocity Contours and Radial Profiles at x = 10d